ERDC/CHL TR-09-2

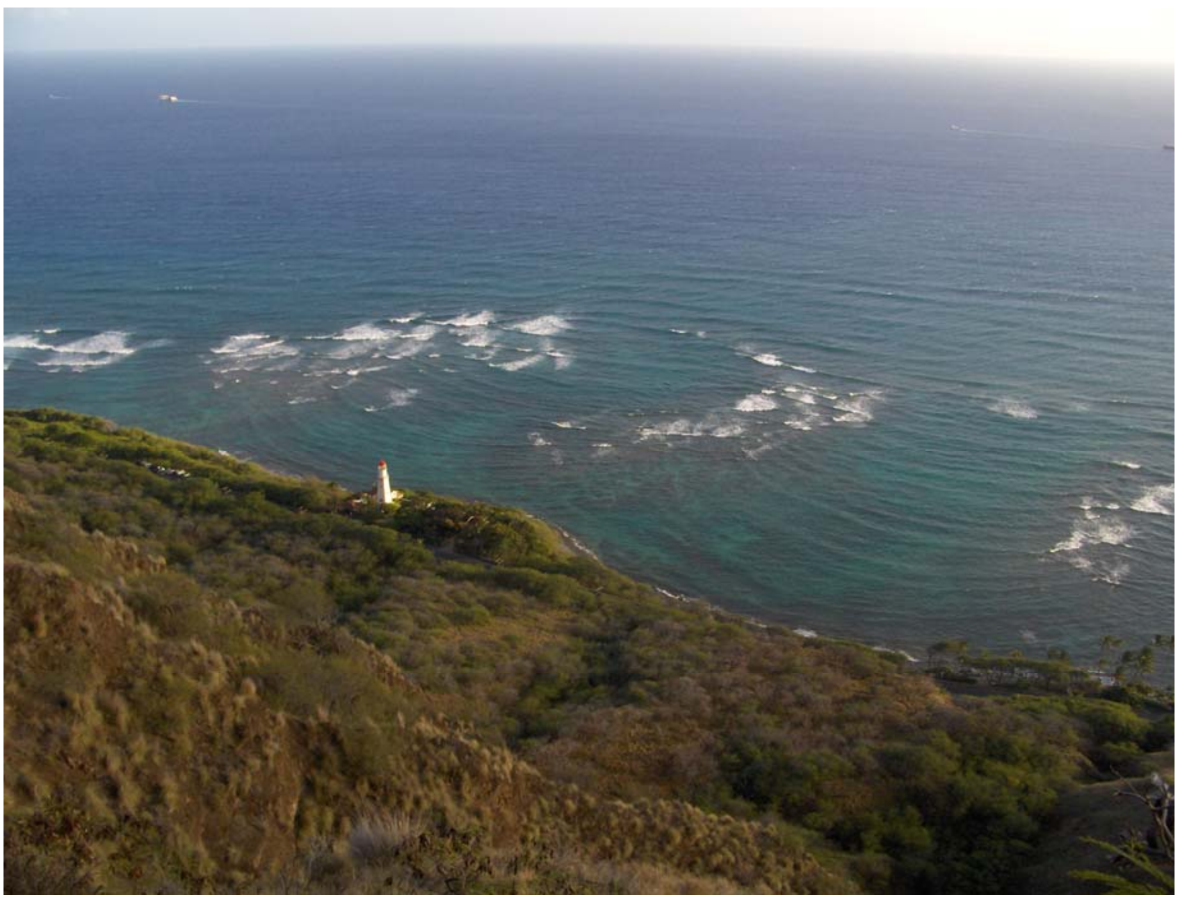
Coastal and Hydraulics Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Surge and Wave Island Modeling Studies
Coastal Field Data Collection Program

TWAVE: A Modeling System for Flooding and Inundation of Islands by Tropical Storms

Alejandro Sánchez, Zeki Demirbilek, and Jane M. Smith January 2009



Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JAN 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **TWAVE: A Modeling System for Flooding and Inundation of Islands by Tropical Storms**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineer Research and Development Center,Coastal and Hydraulics Laboratory,3909 Halls Ferry Road,Vicksburg,MS,39180-6199**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**89**	

ERDC/CHL TR-09-2
January 2009

TWAVE: A Modeling System for Flooding and Inundation of Islands by Tropical Storms

Alejandro Sánchez, Zeki Demirbilek, and Jane M. Smith

Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199, USA

Final report

Prepared for Headquarters, U.S. Army Corps of Engineers
Washington, DC 20314-1000

Monitored by Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

Abstract: This report, the first of a series, describes the coastal modeling package TWAVE (Typhoon and WAVE) developed under the Surge and Wave Island Modeling Studies (SWIMS) project capable of modeling tropical cyclone winds, waves, storm surge, and coastal inundation. The TWAVE flood and inundation package is a practice-oriented engineering modeling tool. The first version of TWAVE is described in this report and will be updated based on user feedback in subsequent reports and as new modeling capabilities become available. The objective of this research is to develop a system with multiple levels of complexity that is suitable for applications such as hindcast, forecast, and hypothetical storms. TWAVE is a personal computer based modeling system and uses Microsoft Excel® to organize and visualize input and output data. The package includes three wind models coupled to a deepwater spectral wave model and a parametric wave model with several options for calculating reef top wave heights, wave setup, and runup. These calculations range from simple empirical formulations to a fully nonlinear Boussinesq wave model.

TWAVE modeling system is currently configured for the U.S. Territory of Guam and the island of Kauai, HI, but can easily be configured for other locations. A full description of the TWAVE package of programs and input, and output are described in this report to assist users who interested in adopting the system to their specific needs. TWAVE is a modular system, and this makes it possible to add new components and replace existing modules as necessary. TWAVE modeling package is validated using measured offshore winds and waves, and coastal inundation records for Hurricane Iniki at Poipu beach on the island of Kauai, HI. Modeling estimates generally compare reasonably well with measurements. The calculated offshore winds, waves, and coastal inundation estimates compare favorably to data. Although there were no data for validation on the island of Guam, TWAVE capabilities are also demonstrated for Typhoon Russ.

Contents

Figures and Tables

Figures

Tables

Preface

The Surge and Wave Island Modeling Studies (SWIMS) of the Coastal Field Data Collection Program is developing a coastal modeling package called TWAVE for tropical environments such as the Hawaiian Islands and territory of Guam. TWAVE consists of a set of numerical models for island coastal inundation, and is intended as a predictive tool for the U.S. Federal and State civil defense agencies and the U.S. Army Corps of Engineers District Offices. This report describes the theory and implementation of TWAVE and contains examples that demonstrate its purposes. The modeling package components are described, step-by-step instructions are provided on how to run each numerical model component of TWAVE and view modeling results.

This report was prepared by Dr. Zeki Demirbilek and Alejandro Sánchez, Harbors, Entrances, and Structures Branch, and Dr. Jane M. Smith, Coastal Processes Branch, Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS. J. Holley Messing, Coastal Engineering Branch, Navigation Division, CHL, typed the equations and format-edited the draft report. Work at CHL was performed under the general supervision of Jose Sanchez (former Chief), and Jackie Pettway (current Chief), Harbors, Entrances, and Structures Branch; Ty Wamsley, Chief, Coastal Processes Branch; Dr. Rose Kress, Chief, Navigation Division; and Bruce Ebersole, Chief, Flood and Storm Protection Division. Dr. William D. Martin was Deputy Director, CHL, and Thomas W. Richardson was Director, CHL.

COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
inches	0.0254	meters
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
square miles (U.S. statute)	2.59	square kilometers
mbar	1.00	hPa

1 Introduction

Overview

Tropical islands may encounter strong wind events due to tropical cyclones which cause severe damage and life-threatening conditions. The capability to quickly forecast the coastal wind and wave conditions for estimating the resulting coastal inundation is crucial for planners and decision-makers responsible for early warnings, evacuations, and relief procedures. Protective coastal measures are commonly based on historical records of the measured surge levels and waves and/or numerical estimates of hypothetical cyclones representative of historical events. One of the challenges in estimating storm-induced coastal inundation is the reliability of predicting the nearshore waves. This requires using nonlinear wave models such as Boussinesq-type fully nonlinear models to obtain reliable estimate of waves, wave setup and wave runup on coastal areas of islands. Because these two-dimensional (2D) models are computationally demanding, an alternative is to use simpler one-dimensional (1D) models to simulate wave transformation over several transects along the coastlines that are of concern for flood inundation. Nwogu (2006) obtained consistent wave runup using 1D and 2D Boussinesq wave model simulations of nearshore waves during Hurricane Iniki along the coast in Kauai, HI. The 1D models have been used extensively and successfully in calculating waves in the surf zone (e.g., Gerritsen 1980; Thornton and Guza 1983; Stive and De Vriend 1994; Massel and Gourlay 2000; Massel and Brinkman 2001; Gourlay 2005).

Over the past decade, the Coastal and Hydraulics Laboratory (CHL) of the U.S. Army Engineer Research and Development Center (ERDC), has developed and improved numerical modeling procedures for determining coastal waves and inundation for tropical storms (e.g., Luettich et al. 1992; Smith 1993; Thompson and Cardone 1996; Smith et al. 2001; Thompson and Scheffner 2002; Thompson 2005; Demirbilek et al. 2007; Demirbilek and Nwogu 2007; Demirbilek et al. 2008). The Surge and Wave Island Modeling Studies (SWIMS) project of the U.S. Army Corps of Engineers (USACE) is developing predictive capabilities for island flood estimates. One of these tools is a simple, first-order integrated wave modeling package, called TWAVE (Sánchez et al. 2007). TWAVE is intended for the U.S. civil defense agencies and USACE District Offices, providing users a practice-oriented package which is user-friendly, flexible, robust, and suitable for the feasibility and reconnaissance type of engineering planning studies. This is a manual for the TWAVE model, not a full assessment of the model's abilities, which is a task that is just beginning, now that the model is operational. The TWAVE modeling system is expected to evolve and be improved as it is used in engineering projects. TWAVE will be calibrated with additional field observations in progress. Other numerical models and different engineering methods may be incorporated into TWAVE as these validations warrant.

The missions and areas of responsibility for the USACE include many islands in the tropical Pacific Ocean, Atlantic Ocean, and Caribbean Sea. These islands typically have narrow coasts, rugged interiors, and coastal roads and communities that are a vital part of the islands economy, transportation, and safety. Many island coasts are exposed to long-period swells from extratropical storms generated in both the northern and Southern Hemisphere, and are occasionally impacted by powerful tropical storms. Despite the presence of protective coral reefs, elevated water levels caused by wave setup, winds, and low atmospheric pressure during storms cause waves to run-up on shore and cause damage to island roads and communities.

Previous studies employed a stream of up to ten different engineering models. These Fortran programs had to be run sequentially, and results were visualized using external commercial plotting software packages. The stream of programs begins with calculating wind fields and ends with calculation of the water levels and maximum runup levels at user-selected transects along a section of the islands coast. The set of stand-alone models has been integrated into a user-friendly island flood and inundation modeling package called "TWAVE," an acronym for Typhoon and WAVE modeling package. The TWAVE system is implemented in a Microsoft Excel® workbook that serves as the graphical-user-interface (GUI) for data management, program execution, and visualization and analyses of results. Microsoft Excel was chosen because it provides a convenient interface for the package, readily available on desk-top computers, and is commonly used by potential users of the TWAVE from Federal, State, and local agencies. This gives users the flexibility to edit existing plots and adapt graphics to fit their special needs.

The TWAVE flood and inundation package is a practice-oriented engineering modeling tool. The first version of TWAVE described in this report is expected to evolve based on its utility for Federal, State, and local agencies. The objective is to provide planners, decision-makers, and engineers with a predictive modeling tool by making it available in the simplest form possible. TWAVE provides users the power of present numerical modeling technology, places it directly in their hands, and allows them to apply it to real-world scenarios. This framework allows model developers to refine and expand the package into a more comprehensive tool for future needs. Although the first release of TWAVE has been configured for the U.S. Territory of Guam and the island of Kauai, HI, the modeling package is general and can be adapted for application to other islands.

The water depth, wave sheltering, and shoreline orientation are needed for calculation of the nearshore waves in TWAVE. Wave runup and inundation calculations require cross-shore bathymetric profiles. Users can define an arbitrary number of nearshore stations and runup locations by providing these required data. Future versions of TWAVE will include a database of pre-computed cross-shore profiles and enhanced numerical modeling features and capabilities as options for these calculations. Although TWAVE is intended for modeling storm waves for flooding and island inundation works, it may also be used for the transformation of swell and extratropical storm waves in the nearshore region for other engineering projects.

Modeling package

The modeling approach in TWAVE is a multi-level approach, in which users have the option of running different models with varying accuracy, resolution, and computational time. Figure 1 shows a flowchart of the TWAVE modeling system and components as described in this report (blue text). The components that will be added in future releases are shown in red. Many of the modeling components in TWAVE are similar to those described by Thompson and Scheffner (2002) and Militello et al. (2003). However, in this first release of TWAVE, the storm surge is approximated by a barometric tide calculated based on the atmospheric pressure. Such a simple tide calculation method eliminates the need of using a computationally-intensive circulation model. This method is considered adequate for most tropical islands that lack wide continental shelves that can alter the storm surge signal. Subsequent versions of

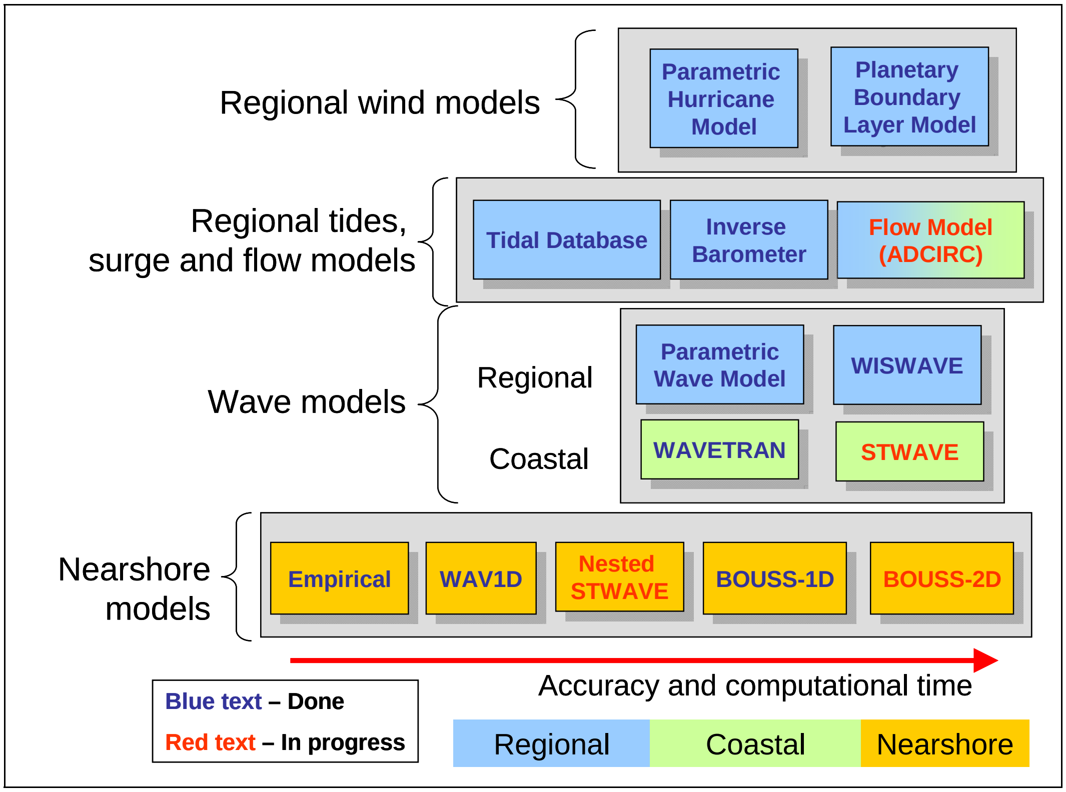


Figure 1. TWAVE modeling approach.

TWAVE will include circulation models for calculating the combined storm surge and astronomical tides. Parametric wind and wave models are used for fast computations as required within the TWAVE system.

More emphasis is given to detailed modeling of nearshore wave processes that determine the extent of island flooding and inundation. Consequently, a wave energy flux model and an advanced 1D Boussinesq model are included in the TWAVE system for reliable estimate of nearshore wave transformation, setup, and runup. TWAVE has input/output (I/O) files associated with different numerical models used in the package. Users do not need to be concerned about most of these files, but the names and their connectivity with other programs are described in this report. This information should help users to independently run specific components of TWAVE such as the tide model only if so desired. An overview of the TWAVE main modeling components is provided in this report, including a description of the individual programs, processing subroutines, and input and output. All input parameters and data used in TWAVE are in SI units, and times are the Greenwich Mean Time (GMT).

The layout of this report is as follows. Wind modeling is described in Chapter 2. The astronomical tide database used in TWAVE is reviewed in Chapter 3. Wave models are presented in Chapter 4. The TWAVE package including its Excel® interface and I/O files are described in Chapter 5. The procedure for running TWAVE is described in Chapter 6. Two example applications are provided in Chapter 7. The summary and conclusions are discussed in Chapter 8. References section provides additional information as referenced in the body of this report.

2 Regional Wind Models

Wind and atmospheric pressure

Three methods are available in TWAVE for calculating the time-history of wind and atmospheric pressure. The first method uses the Planetary Boundary Layer (PBL) model and the other two use the parametric Holland and Rankin Vortex models. The key features of each model are briefly discussed next.

In the PBL model, the effect of marine boundary layer is considered by relating the surface stress to the geostrophic flow over the ocean surface. The PBL as used in TWAVE, takes a synoptic-scale pressure field to calculate the surface geostrophic flow from it, and then adjusts (corrects) it for the curvature effects of isobars (gradient wind effects). To account for stratification above the sea surface, the air-sea temperature differences, surface roughness, and moisture due to wave generation by wind stress have been included in the PBL governing equations (Cardone et al. 1992; Thompson and Cardone 1996). A brief summary of the PBL model follows.

When less accuracy is required (e.g., simulating hypothetical storms in engineering applications that do not require high accuracy), parametric hurricane models offer a simpler and faster approach to estimate winds and pressure fields generated by tropical storms. The simulation time for the PBL model is several minutes, and additionally PBL requires pre- and post-processing, while the run time for the parametric models is seconds and require no pre- or post-processing. The two parametric wind models used in TWAVE have been shown to provide reasonably accurate wind and pressure estimates (Phadke et al. 2003).

PBL model

The PBL model used in TWAVE is based on the vortex model of Chow (1971) as modified by Cardone et al. (1992) and later Thompson and Cardone (1996). The model simulates wind based on the vertically averaged primitive equations of horizontal momentum in a moving coordinate system as

$$\frac{d\vec{V}}{dt}+f\vec{K}\times\left(\vec{V}-\vec{V}_g\right)=\frac{1}{\rho}\nabla p+\nabla\cdot\left(K_H\nabla\vec{V}\right)-\frac{C_D}{h}\left|\vec{V}+\vec{V}_c\right|\left(\vec{V}+\vec{V}_c\right) \tag{1}$$

where:

$\vec{V}$ = horizontal wind velocity vector relative to the storm center
$\vec{K}$ = unit vector
$\vec{V}_g$ = constant geostrophic velocity vector relative to the storm center
ρ = mean air density
p = atmospheric pressure
K_H = horizontal eddy viscosity
C_D = drag coefficient
h = elevation of the PBL model
$\vec{V}_c$ = velocity vector of the storm.

The vertical advection of momentum and the shear stress at the top of the PBL are assumed to be small and ignored. The model includes parameterizations for momentum, heat and moisture fluxes, and a formulation for surface roughness and drag. The pressure field is calculated using the exponential pressure law,

$$p=p_c+\Delta P\exp\left(-R_{\max}/r\right) \tag{2}$$

where r is the radial distance and $R_{\max}$ is the radius of maximum winds. The PBL model implements five nested sub-grids and a moving coordinate system so that the center of the storm is always in the center of the domain. The model has been shown to accurately model surface wind speeds and directions for tropical storms over open water (Thompson and Cardone 1996). For Guam and Hawaii, the largest grid is configured to cover a region of 8 by 8 deg (890 by 890 km) with a 5-min (9.3 km) resolution. The five sub-grids have 12 nodes in the x and y directions with varying resolutions.

Holland model

This parametric model provides estimates of the wind and pressure based on the maximum sustained wind speed, the radius of maximum wind speed, and a peakedness parameter. The advantage of this model is that it is fast and gives reasonable estimates of both wind and pressure. Wind velocities are calculated from the pressure distribution using a pressure gradient wind balance (Holland 1980) given by

$$V = \left(V_c^2 + \frac{r^2 f^2}{4} \right)^{1/2} - \frac{r|f|}{2} \tag{3}$$

where f is the Coriolis parameter defined as $f = 2\Omega \sin \varphi$, where Ω is the earth's angular rotation in radian/sec and φ is the latitude in degrees. V_c is the cyclo-strophic wind speed in m/sec obtained from the pressure field as

$$V_c = \left[R^{-B} \frac{\Delta P}{\rho} \exp\left(-R^{-B}\right) \right]^{1/2} \tag{4}$$

where:

B	=	peakedness scaling parameter
R	=	normalized radial distance ($R = r/R_{max}$)
R_{max}	=	radius of maximum winds
P	=	pressure at radius r
ρ	=	mean air density
$\Delta P = p_a - p_c$	=	pressure deficit where p_a is the ambient pressure and p_c the central pressure.

The radial variation of atmospheric pressure is given by

$$p = p_c + \Delta P \exp\left(-R^{-B}\right) \tag{5}$$

Note that in Equation 5 the wind speed at $R = 1$ only depends on B and the pressure deficit. Therefore, if both the maximum wind speed and central pressure are available, a reasonable estimate of the scaling parameter can be obtained from Equation 5 by setting $R = 1$ (Xie et al. 2006) as

$$B = \frac{e \rho U_{max}^2}{\Delta P} \tag{6}$$

When only the central pressure is available, an estimate of the scaling parameter can be obtained from the empirical relation of Harper and Holland (1999) as an alternate to Equation 6. The estimate is given by

$$B = 2 - \frac{p_c - 900}{160} \text{ for } 1 < B < 2.5 \tag{7}$$

See the *Control File* discussion in Chapter 5 for additional information for specifying a constant scaling parameter or variable to be used in Equations 6 or 7.

Modified Rankine vortex

In the modified parametric Rankine vortex model (Rankine 1901), the distribution of the wind speed is related to the normalized radial distance R and the shape factor X as follows:

$$V = \begin{cases} U_{\max} R^{X} & \text{for } R < 1 \\ U_{\max} R^{-X} & \text{for } R \geq 1 \end{cases} \tag{8}$$

where $U_{\max}$ is the maximum surface wind speed which occurs by definition at $R = 1$ and $R = r/R_{\max}$. Hughes (1952) has shown that the empirical shape parameter X (exponent of R) ranges from 0.4 to 0.6. The shape parameter in Equation 8 is different from that of the Holland model (Equation 4). In TWAVE, the default value of $X = 0.5$ is used, and this value can be changed by the user in the *Control File* using the variable *xRankine*. This model has been previously shown to provide reasonable wind estimates for the Hawaiian Islands (Phadke et al. 2003).

Wind corrections for forward motion and inflow

In the Northern Hemisphere, tropical storms have stronger winds on the right side and weaker winds on the left side of the forward direction of the storm. In order to simulate this asymmetric wind pattern, a correction was added to the wind speed (Georgiou 1985) which takes into account the forward velocity of the storm as

$$V_F = 0.5 V_f \sin\beta \tag{9}$$

where V_f is the hurricane forward velocity and β is the direction of any location (each isobar's tangent angle) with respect to the hurricane translation direction.

In the parametric wind models, the wind direction in the Northern Hemisphere has a counter-clockwise rotation and is approximated by a tangent to the isobars. This requires the wind direction to be corrected for the wind isobars that are close to the center of the storm (core flow or inner flow region). An appropriate correction was suggested by Bretschneider (1972) by subtracting the following correction from each isobar's tangent angle:

$$\beta = \begin{cases} 10^{o}\left(1+\dfrac{r}{R_{\max}}\right), & 0 \le r \le R_{\max} \\ 20^{o}+25^{o}\left(\dfrac{r}{R_{\max}}-1\right), & R_{\max} \le r \le 1.2R_{\max} \\ 25^{o}, & R_{\max} \ge r \end{cases} \tag{10}$$

Parameterizations of storm characteristics

The simulation of wind and pressure fields in TWAVE requires specifying storm track coordinates in degrees north and east, and 1-min maximum sustained wind speed in knots. The storm central pressure (mbar) and radius of maximum wind speed (km) are optional. If the central pressure is not available (denoted by -99), the central pressure is calculated by one of two formulas given in Equations 11 or 12. One of the most commonly used formulations is by Atkinson and Holliday (1985),

$$U_{\max} = 3.45\left(1010 - p_c\right)^{0.644} \tag{11}$$

Knaff and Zehr (2007) evaluated several wind-pressure relationships and determined that $U_{\max}$ calculated using Equation 11 had a negative bias. Therefore, the functional form of Koba et al. (1990) is used in TWAVE as

$$\Delta P = 6.22 - 0.58U_{\max} - \left(U_{\max}/31.62\right)^{2} \tag{12}$$

The user can either use Equations 11 or 12 by selecting the toggle *centrpres* in the TWAVE *Control File* (Chapter 5).

The radius of maximum wind speed $R_{\max}$ is used to estimate the size of the storm. If $R_{\max}$ is not available (denoted by -99), the empirical relation of Willoughby et al. (2006) is used to estimate this parameter as

$$R_{\max} = 46.4 \exp\left(-0.0155 U_{\max} + 0.0169 \varphi\right) \quad (13)$$

where φ is the latitude in degrees. Equation 13 is valid only for the Northern Hemisphere. Storm track positions, wind speeds, central pressures, and radius of maximum wind speed are read at 6-hr intervals and interpolated hourly estimates are calculated by a cubic-spline fit.

3 Astronomical Tides

The astronomical tides affect water levels, which in turn influence the storm surges and waves causing flooding of island shorelines. In TWAVE, tidal water elevations are computed using the Oregon State Tidal Prediction Software OTPS (http://www.coas.oregonstate.edu/research/po/research/tide/otis.html), which operates on a pre-calculated tidal database. Two global and one regional (Hawaiian Islands) tidal databases are developed. These tidal solutions were calculated using the Oregon State Inversion Software called OTIS (Egbert and Erofeeva 2002). The tide water levels and velocities are calculated with a least-squares fit of along track average TOPEX/Poseidon and Jason altimeter data to the Laplace Tidal equations. Eight primary (M2, M4, S2, N2, K1, O1, P1, and Q1) and two minor long-period harmonic constituents (Mf and Mm) are provided as complex amplitudes on a grid with ¼-deg resolution for the global tide database (TPXO7.1) and 1/30-deg for the regional Hawaiian Islands database (Haw). Additional solutions for specific regions may be downloaded from http://www.coas.oregonstate.edu/research/po/research/tide/region.html, and placed in the folder called OTIS/DATA/.

The OTPS software has been implemented in TWAVE by adding programs that prepare OTPS input files and convert output files named Astronomical Tides File for TWAVE to use. These ASCII files contain hourly tidal predictions at Nearshore Stations. Other tidal prediction models or databases may be incorporated in TWAVE to generate the Astronomical Tide Files. For more information on the file format, how to specify the tidal solution name, and other input parameters, see Chapter 5.

4 Waves

Deepwater wave models

Two models are included in TWAVE for calculating the deepwater waves. The first is a spectral wave model and the second is a parametric model.

Spectral wave model

The second-generation spectral wave model WISWAVE (Wave Information Studies WAVE model) is implemented in TWAVE to simulate deepwater wave generation, growth, propagation, dissipation, and transformation (Hubertz 1992; Resio and Perrie 1989). WISWAVE solves the discrete form of the unsteady wave energy balance equation in two dimensions as

$$\frac{\partial N}{\partial t} + C_g \cdot \nabla N = \sum_{i=1}^{n} S_i \tag{14}$$

where N is the wave action density (energy density/frequency), t is time, C_g is the group velocity, and S_i are the source/sink functions for wind input, whitecapping dissipation, and nonlinear wave-wave interactions. Tracy and Cialone (2004) showed comparable results between WISWAVE and a third-generation wave model for wave hindcast in the Gulf of Mexico. Wind fields are input at 1-hr intervals. The model output at selected grid points consists of wave parameters (wave height, peak and mean wave period, and mean wave direction) and percent total energy in each frequency band of the wave spectra. The grid points can be either entered in the *WISWAVE Options File* or in the *Offshore Stations File*. The *Offshore Stations File* is used if no stations are specified in the *WISWAVE Options File*. WISWAVE is setup in TWAVE to use the large PBL model grid.

Parametric wave model

The WISWAVE spectral wave model is the most computationally intensive model in the TWAVE package. A simpler and faster model is adequate for planning studies and for simulation of hypothetical storms. Therefore, a parametric hurricane wave model (Bretschneider 1972) is also implemented in TWAVE. This model assumes a constant wave height distribution based on a slow moving hurricane assumption. The deepwater maximum wave height and peak period are calculated every hour based on the following empirical relations at the point of maximum winds as

$$H_s = 5.03 \exp\left(\frac{R_{\max} \Delta P}{4700}\right)\left[1 + \frac{0.29 \alpha v_f}{\sqrt{U_R}}\right] \tag{15}$$

$$T_s = 8.6 \exp\left(\frac{R_{\max} \Delta P}{9400}\right)\left[1 + \frac{0.145 \alpha v_f}{\sqrt{U_R}}\right] \tag{16}$$

where U_R is the maximum sustained wind speed in m/sec at 10-m elevation, $R_{\max}$ is the radius of maximum wind in km, ΔP is the difference between the normal atmospheric pressure and the central pressure of the hurricane specified in mm of mercury, v_f is the forward velocity of the hurricane in m/sec and α is an empirical coefficient assumed to be 1.0. The spatial distribution of wave height is calculated using the contour values and the coordinates with respect to the forward direction of the storm (Figure 2).

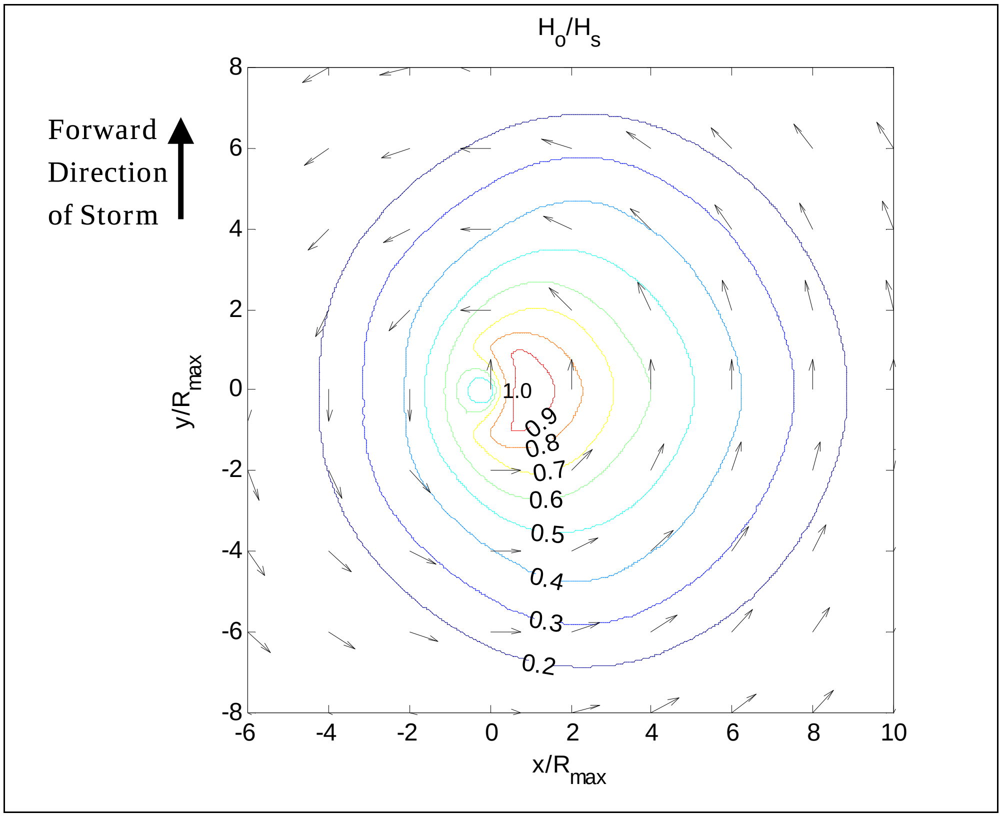


Figure 2. Normalized deepwater significant wave height for slow moving hurricane.

The wave period is estimated as

$$T_o = 12.1\sqrt{H_o / g} \tag{17}$$

The wave direction is perpendicular to the radial from the hurricane center (Figure 2). Although the parametric wave model is fast, it may not be appropriate for forecasting or hindcasting storms because it approximates many physical processes governing the generation and growth of deep-water waves. It does not account for wave propagation and therefore underestimates waves that are more than approximately 3 $R_{\max}$ away from the storm center. It is recommended that this model only be used for stations near the storm eye and for hypothetical events for which the uncertainty of input parameters is greater than those of historical events.

Deep- to shallow-water wave transformation

The deepwater wave estimates from offshore are transformed to nearshore using the Wave Information Study (WIS) Phase-3 transformation model WAVTRAN (Jensen 1983; Gravens et al. 1991). The wave spectra are transformed based on the shoreline orientation with respect to the incident waves, the change in water depth, and sheltering effects. WAVTRAN assumes straight and parallel bathymetric contours and uses an input TMA spectral shape (Bouws et al. 1985). Sheltering is considered by removing the wave energy from sheltered grid points (wave directions that are sheltered by land). The directional spreading function is assumed as a cosine to the 4th power angular distribution.

Nearshore wave models

The term nearshore here refers to the coastal region from intermediate ($0.05 < h/L < 0.25$) to shallow water ($h/L < 0.05$) where h is water depth and L is wavelength, and in which waves shoal, refract, and break. The nearshore water, relative to the mean sea level (MSL), includes a still water level (SWL) component (astronomical and barometric tide plus wind-driven surge) and wave setup component (driven by momentum lost from the waves as they break. Figure 3 shows a schematic of a fringing reef and a typical wave setup distribution across the reef. Wave runup is the elevation of highest wave excursion relative to the SWL (thus, it includes the setup). Inundation refers to the horizontal distance landward from the shoreline to the farthest inland reach of the water level with the wave runup.

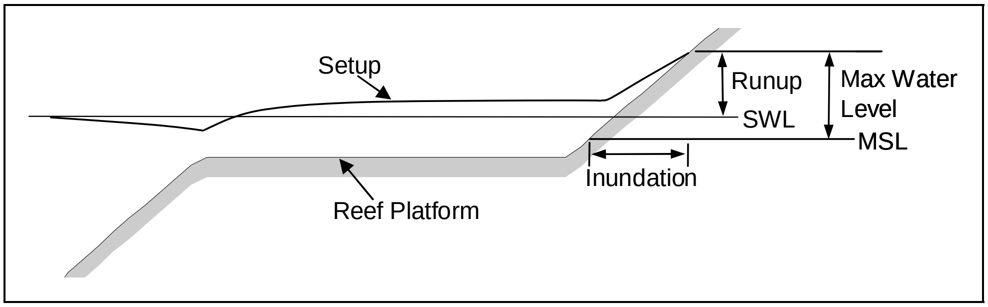


Figure 3. Schematic of fringing reef profile and variable definition.

Note that the runup and inundation are defined with respect to the SWL while the max water level is equal to the runup level with respect to the MSL.

The nearshore wave transformation is calculated at hourly intervals on predefined transects that are approximately normal to shore. There are four options for calculating wave heights and water levels over the reef. All methods use the same incident nearshore wave heights and water levels, but vary in their complexity and the amount of input information required. The first two methods are used when the bathymetric profile is not available. Method 1 calculates the wave height over the reef by assuming a stable wave height and calculates reef top water levels using simple empirical formulas for wind and wave setup. The second method calculates the cross-shore wave height variation using a simple energy flux method, but also uses the same empirical formulas as Method 1 to calculate reef top water levels. The third method is a steady-state model which solves the 1D wave energy conservation and momentum equations. The last method is a time-dependant nonlinear wave model based on the Boussinesq equations (Demirbilek et al. 2008; Demirbilek and Nwogu 2007). Methods 1-3 are calculated within the program *reefwave_TW.exe* at hourly intervals while Method 4, the Boussinesq wave model, is run using a separate batch file (run_bouss1d.bat). These methods are briefly discussed next.

Method 1: Empirical formulas

Because many coral reefs are characterized by wide shallow platforms, wave heights over the reef are usually depth limited. Therefore, the wave height estimate will also be fairly accurate as long as the mean water depth over the reef top can be estimated reasonably accurately. The setup on the reef platform is separated into wave and wind components $\Delta\eta = \Delta\eta_{wave} + \Delta\eta_{wind}$. The procedure for calculating wave setup over the reef is as follows. First, the reef platform water depth is adjusted for wave setup using an empirical equation and then the wind setup is calculated using semi-analytical equation.

Earlier research studies (Seelig 1983; Gourlay 1996a, 1996b) have shown that the reef top wave setup decreases with the still water depth, increases with the offshore wave power, and decreases with increasing wave steepness. Using these findings, Sánchez et al. (2007) developed an expression to estimate wave setup over fringing reef profiles similar to that of Seelig (1983) as

$$\Delta\eta_{wave} = -0.18 h_r + 0.48 \log_{10}\left(H_o^2 T\right) - 5.53 H_o / T^2 \tag{18}$$

where h_r is the still-water depth on the reef top. For fringing reefs, most of the wave setup occurs in a narrow region near the reef edge where the waves break and lose a large portion of their energy and momentum. The wind setup over the reef platform can be estimated from the momentum balance over the reef as

$$\rho g d_{wr} \frac{\partial \eta}{\partial x} = \tau_{wx} \tag{19}$$

where $d_{wr} = h_r + \Delta\eta_{wave}$ and τ_{wx} is the wind stress in the x-direction defined as $\tau_{wx} = \rho_a C_d |U| U$. Here ρ_a is the air density, U is the wind velocity in the x-direction (cross-shore), and C_d is the wind drag coefficient. Therefore, by assuming that $\Delta\eta_{wave}$ remains constant over the reef top and following Bretschneider (1966), Equation 19 can be integrated over the width of reef W to give an expression for the wind setup over the reef platform given by

$$\Delta\eta_{wind} = -d_{wr} + \sqrt{\alpha_s W U^2 + d_{wr}^2} \tag{20}$$

where $\alpha_s \approx 2\rho_a C_d/(g\rho)$. Although the wind setup is usually small compared to the wave setup, during storms and for wide shallow reefs, the wind setup can be significant. Figure 4 shows a comparison of measured and calculated setup over a fringing reef profile from laboratory experiments of winds and waves (Demirbilek et al. 2007). In this reef example, the wave setup has been calculated with Equation 18 using waves-only experimental conditions. The wind setup from Equation 20 is added to calculate the total setup on the reef top. As can be seen from Figure 4, including the wind setup significantly improves the comparison between predicted and measured setup on the reef. Calculated wave setup for the reef profiles used by Seelig (1983) and Gourlay (1994) are also included in Figure 4.

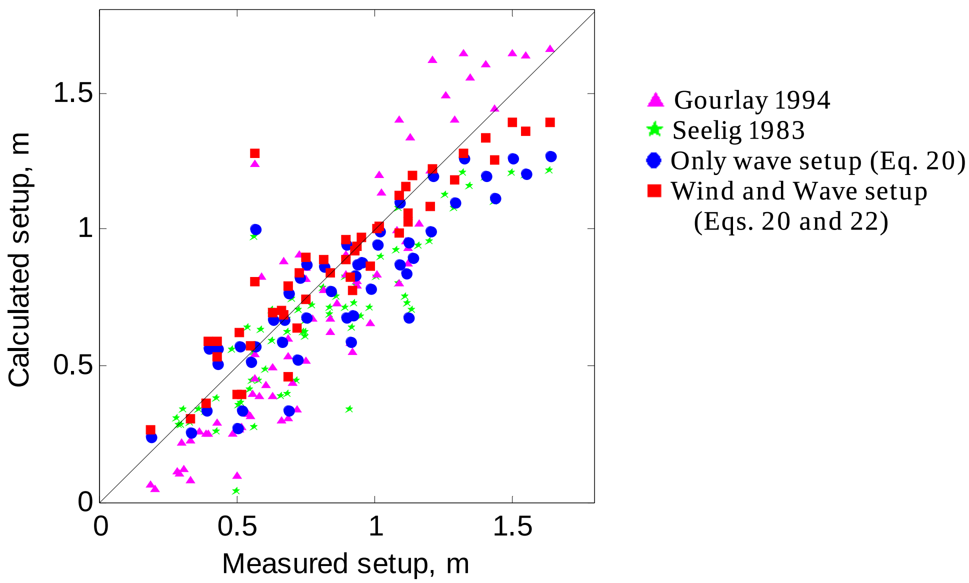


Figure 4. Comparison of various empirical formulas for setup over fringing reef to laboratory measurements of Demirbilek et al. (2007).

The stable wave height over the reef is estimated from the depth-limited $\gamma = H_{rms}/d \approx 0.4$ (Dally et al. 1985). This estimate may not be valid in many applications such as relatively large waves over narrow reefs or conversely relatively small waves over wide reefs. The width of the reef platform is considered in Method 2. Method 1 is used when the user specifies a water depth over the reef top but does not provide a reef platform width.

Method 2: Simplified geometry and wave model

In situations where the reef is narrow or very wide, it is important to consider the spatial variation of wave height over the width of the reef. In this approach, the wave and wind setup are calculated as in Method 1 to obtain the water level over the reef. The wave height is then propagated over the reef using a simple energy flux method and the wave breaking formulation of Dally et al. (1985) (see description of Method 3 for further details). In this approach the water depth over the reef is not coupled to the wave energy flux. This is the approach used in Method 3. The wave height at the offshore end of the reef top can be either set to a breaking wave height using the empirical equation of Komar and Gaughan (1973) where $H_b = 0.39(H_o/L_o)^{-0.2}$ (where H_o is deepwater wave height and L_o is deepwater wave length), or set to the nearshore wave height. This option is controlled using the toggle *ibreak*, within the TWAVE *Control File*. See Chapter 5 for further details on TWAVE *Control File*.

Method 3: Wave energy flux model (WAV1D)

A number of different type of 1D models based on the conservation of wave energy flux and momentum have been used extensively and successfully in calculating wave transformation and water levels in the surf zone (Gerritsen 1980; Thornton and Guza 1983; Dally et al. 1985; Dally 1992; Larson and Kraus 1991; Massel and Brinkman 2001; Grasmeijer and Ruessink 2003). There are two approaches that can be used in 1D energy flux models. Single wave models (e.g., Dally et al. 1985) simulate the wave transformation of a representative or characteristic wave height, wave period, and direction, while probabilistic models simulate wave transformation based on a discrete number of wave classes (e.g., Larson and Kraus 1991). Grasmeijer and Ruessink (2003) compared single wave and probabilistic models to laboratory and field measurements. They concluded that the single wave models was simpler and faster, and produced similar error statistics to the probabilistic models. A single wave approach is used in TWAVE.

Assuming alongshore uniformity in the bathymetry, the time-averaged wave energy balance equation may be written as

$$\frac{\partial}{\partial x}(EC_g \cos\theta) = D_b + D_f \tag{21}$$

where E is the wave energy density per unit area, C_g is the wave group velocity, θ is the incident wave angle relative to shore normal, and D_b and D_f are the wave energy dissipation due to breaking and bottom friction, respectively. By assuming that the individual wave heights follow a Rayleigh distribution (Headquarters (HQ) USACE 2006) given by

$$p(H) = \frac{2H}{H_{rms}} \exp\left[-\left(\frac{H}{H_{rms}}\right)^2\right] \tag{22}$$

where H_{rms} is the root-mean-squared (rms) wave height, and the wave energy density is then defined as

$$E = \frac{1}{8}\rho g \int_0^\infty H^2 p(H) dH = \frac{1}{8}\rho g H_{rms}^2 \tag{23}$$

The significant wave height is estimated as $H_s = \sqrt{2} H_{rms}$. The wave dissipation due to bottom friction is calculated as

$$D_f = \frac{\rho f_w}{12\pi}\left(\frac{2\pi H_{rms}}{T \sinh(kd)}\right)^3 \tag{24}$$

where f_w is the wave-related friction coefficient given by

$$f_w = \min\left\{0.3, \exp\left[-6.0 + 5.2\left(A_b / k_w\right)^{-0.19}\right]\right\} \tag{25}$$

where A_b is the near-bed wave orbital excursion calculated from linear wave theory and k_w is a hydraulic roughness length assumed to be equal to the physical roughness (Nielson 1992). Lowe et al. (2005) estimated the hydraulic roughness along several transects of a coral reef and found $k_w = 0.16 \pm 0.03$. Gerritsen (1980) suggested values between 0.025-0.125. Demirbilek and Nwogu (2007) considered reef roughness in terms of the Chezy friction factor, and their equivalent values to the f_w friction coefficient ranged from 0.01 to 0.15.

Because the wave breaking term in Equation 21 is the dominant term in the surf zone, the estimated wave results are sensitive to the wave breaking formulation being used. Two types of formulations can be used to estimate the breaking wave dissipation. The first formulation adopted for wave breaking dissipation is based on the work of Battjes and Janssen (1978). Recently, Alsina and Baldock (2007) and Janssen and Battjes (2007) independently obtained the following expression for wave breaking dissipation as

$$D_b = \frac{3\sqrt{\pi}}{16}\rho g B \frac{1}{T}\frac{H_{rms}^3}{d} Q_b \tag{26}$$

where B is the wave breaking intensity factor, and the fraction of broken waves Q_b is estimated as

$$Q_b = 1 + \frac{4}{3\sqrt{\pi}}\left(R^3 + \frac{3}{2}R\right)\exp\left(-R^2\right) - \mathrm{erf}(R) \tag{27}$$

In Equation 27, erf is the error function and $R = H_b/H_{rms}$, and the breaking wave height is obtained from H_b = 0.88 tanh $(\gamma kd/0.88)/k$. The breaker index γ is calculated using the expression of Battjes and Stive (1985) $\gamma = H_b/d$ = 0.5 + 0.4 tanh (33 H_o/L_o) (Alsina and Baldock 2007), where d is local water depth, and k is wave number.

Equation 26 is obtained by following a similar approach as in Battjes and Janssen (1978) without assuming a truncated Rayleigh distribution (e.g., using a complete Rayleigh distribution). The default coefficients in Equation 26 may be changed in the TWAVE *Control File*. Alsina and Baldock (2007) compared Equation 26 to the breaking formulations of Thornton and Guza (1983), Baldock et al. (1998), and Ruessink et al. (2003) and found that Equation 26 produced small errors for steep slopes. Sánchez et al. (2007) compared several breaking formulations for coral reef profiles and found that Equation 26 produced the best results. Therefore, Equation 26 is the default breaking formulation implemented in TWAVE. The second breaking formulation used in TWAVE is the empirical model of Dally et al. (1985) expressed as

$$D_b = \frac{\kappa}{d}\left[EC_g - \min(E, E_s)C_g\right] \tag{28}$$

where κ is an empirical decay coefficient and E_s is the energy associated with the stable wave height defined as

$$E_s = \frac{1}{8}\rho g(\Gamma d)^2 \tag{29}$$

where Γ is the stable wave height normalized by the water depth. Following earlier works (Dally et al. 1985; Smith 1993; Demirbilek and Panchang 1998; Zhao et al. 2001), we adapt 0.15 and 0.42 for the values of κ and Γ. This approach has been used successfully in modeling wave transformation over irregular bathymetry including reefs (Gerritsen 1980; Dally 1992).

Equation 28 does not depend on the wave period and height distributions. The wave height distribution is used only to obtain a characteristic wave height from the wave energy. Equation 28 works best for monochromatic waves because it was developed from laboratory studies of monochromatic waves.

Equation 21 is solved simultaneously with a time-averaged and depth-integrated 1D momentum equation to obtain the combined wind and wave setup over the reef-top and the model is called WAV1D (Demirbilek et al. 2008). Assuming uniformity in the alongshore direction (y-direction) and ignoring mixing and cross-shore currents, the 1D cross-shore momentum equation (Dean and Dalrymple 1991) may be written as

$$\rho g(h+\eta)\frac{\partial \eta}{\partial x}+\frac{\partial S_{xx}}{\partial x}=\tau_{wx} \tag{30}$$

where η is the wave setup relative to the SWL, h is the still-water depth relative to a specific vertical datum, and S_{xx} is the wave radiation stress in the cross-shore direction. The wave radiation stress is approximated using linear wave theory for an arbitrary wave angle (Longuet-Higgins and Stewart 1964) as

$$S_{xx}=E(n(\cos^2\theta+1)-0.5) \tag{31}$$

where θ is the incident wave angle relative to shore normal and $n = 0.5\ [1 + 2kd/\sinh(2kd)]$. Equations 21 and 30 are solved simultaneously from deep to shallow water.

Demirbilek et al. (2008) provide a comprehensive description of the WAV1D model, with four example applications that illustrate the model's performance for wave shoaling, refraction, breaking, and bottom friction compared to data. Sánchez et al. (2007) compared the energy flux model with two laboratory experiments of wave transformation and wave setup over fringing reef-type profiles. They reported average percent errors (average error divided by offshore wave height) of less than 25 percent for wave heights and setup over the reef platform for both waves cases with strong winds. Although WAV1D cannot represent nonlinear transfer of energy in the wave spectrum, it can describe the average wave energy dissipation and wave setup over the reefs. WAV1D is efficient, robust, and works for extreme wave conditions. This makes WAV1D a useful engineering tool for nearshore wave transformation and water levels along cross-shore transects.

Method 4: Boussinesq wave model

BOUSS-1D is a time-dependent, nonlinear, phase-resolving wave model appropriate for estimating nearshore waves, including wave transformation over reefs, wave setup and wave runup. BOUSS-1D is a 1D version of the Boussinesq model BOUSS-2D (Nwogu and Demirbilek 2001; Demirbilek et al. 2005a and b; Demirbilek and Nwogu 2007; Demirbilek et al. 2008). The model solves for the fully nonlinear Boussinesq equations using a finite-difference method and implements a one-equation turbulence closure model to simulate wave breaking in the surf zone (Demirbilek and Nwogu 2007; Demirbilek et al. 2008).

BOUSS-1D models nearshore wave transformation and can simulate wave shoaling, reflection, bottom friction, nonlinear wave-wave and wave-current interactions, wave breaking, wave setup, and wave runup and overtopping of structures. Within TWAVE, the incident waves in BOUSS-1D are assumed to be normal to shore (wave refraction is not considered). The wind setup is included by adding a constant water level estimated by solving Equation 21 across the reef profile. BOUSS-1D is the most accurate of the four methods to calculate nearshore wave transformation and runup. However, it is also the most computationally intensive because it is a nonlinear and time-dependant model. BOUSS-1D inputs are a bathymetry file (*.xy) and a script file (*.gbat) that contains the model input parameters, including wave and water level, and the post processing commands.

Because users of TWAVE will most likely be concerned with the maximum coastal inundation and not its time history, it is not necessary or practical to run BOUSS-1D at hourly intervals for each transect as in the case of the previous methods. BOUSS-1D is run only for the time periods of estimated maximum coastal inundation (runup) from the previous methods. See the BOUSS-1D Input Files section in Chapter 5 for information on how to prepare BOUSS-1D script files. BOUSS-1D is a computationally efficient model, and a typical run time for an 800-m-long transect is approximately 2 min.

Calculation of wave runup statistics

Two methods are used in the estimation of wave runup and inundation statistics in TWAVE. The first method uses empirical formulas embedded within the WAV1D model. The second method applies a zero-crossing analysis to BOUSS-1D runup time series.

Empirical formulas

For design and planning purposes, it is useful to describe the runup in terms of the maximum R_{max} and 2-percent exceedance level $R_{2\%}$ (runup exceeded by 2 percent of waves). $R_{2\%}$ is estimated in three different ways. The first uses an empirical formula from HQUSACE (2006), Equation VI-5-7, applicable for irregular waves on a composite slope as

$$\frac{R_{2\%}}{H_s} = \begin{cases} 1.5\xi\gamma_r\gamma_b\gamma_h\gamma_\beta & \text{for } 0.5 < \xi \le 2 \\ 3.0\gamma_r\gamma_h\gamma_\beta & \text{for } \xi > 2 \end{cases} \tag{32}$$

where:

γ_r = surface roughness factor
γ_b = berm influence factor (= 1)
γ_h = wave height distribution factor (= 1)
γ_β = incident wave angle factor
ξ = surf similarity parameter given by $\xi = \tan\alpha / \sqrt{H_r / L_o}$ where H_r is the wave height over the reef top.

The surface roughness factor is approximately equal to 1.0 for sandy beaches. For more information on the roughness factor refer to the *Coastal Engineering Manual* Table VI-5-3 (HQUSACE 2006). On fringing reefs, waves usually break near or on the reef rim, and waves may reform again over the reef top. This suggests that wave height over the reef top should be used in Equation 32 instead of the deepwater wave height. Wave transformation over reefs is characterized by the presence of infragravity waves generated by non-linear wave energy transfer. For this reason, the deepwater wavelength is used instead of the wavelength over the reef. The incident wave angle factor γ_β is calculated as

$$\gamma_\beta = \begin{cases} 1 & \text{for } 0^\circ < \beta \leq 10^\circ \text{ and } T > 12\,\text{sec} \\ \cos(\beta - 10^\circ) & \text{for } 10^\circ < \beta \leq 63^\circ \text{ and } T > 12\,\text{sec} \\ 0.6 & \text{for } \beta > 63^\circ \text{ and } T > 12\,\text{sec} \\ 1 - 0.0022\beta & \text{for } T < 12\,\text{sec} \end{cases} \tag{33}$$

The second approach used in calculating $R_{2\%}$ is the empirical relation of Mase (1989) for gentle slopes given by

$$\frac{R_{2\%}}{H_s} = 1.86\xi^{0.71} \tag{34}$$

The third approach is the empirical formula of Hedges and Mase (2004) and is given by

$$\frac{R_{2\%}}{H_s} = 0.37 + 1.38\xi \tag{35}$$

The maximum wave runup $R_{\max}$ can be calculated using Mase (1989) as

$$\frac{R_{\max}}{H_s} = 2.32\xi^{0.77} \tag{36}$$

and by Seelig (1983) as

$$R_{\max} = \begin{cases} 1.2 H_s^2 T & \text{for } H_s^2 T \leq 2 \\ 2.4 + 4.189(H_s^2 T - 2)^2 & \text{for } H_s^2 T > 2 \end{cases} \tag{37}$$

Sánchez et al. (2007) found that $R_{2\%}$ and $R_{\max}$, calculated with the empirical runup equations by Mase (1989), were within a 50 percent error of laboratory measurements for fringing profile. Although these empirical methods are approximate, they provide a qualitative and robust means of estimating the largest coastal inundation. The time of maximum coastal inundation or runup may not necessarily occur during the period of largest coastal waves, due to the combined influence of storm surge, tides, wave period and direction, and therefore may vary for different locations around an island. Once the critical time period is identified for each transect, the user may choose to run BOUSS-1D for these times. The TWAVE variable *ir2per* defines which empirical equations for $R_{2\%}$ shall be used. Options are: 0 for Mase (1989); 1 for HQUSACE (2006); 2 for Hedges and Mase

(2004). Similarly, *irmax* defines the equations for R_{max} with options: 0 for Mase (1989), 1 for Seelig (1983). See Chapter 5 for more details on how to use input variables.

Analysis of wave runup time series

In the second method, the 2-percent exceedance level runup $R_{2\%}$ and maximum runup R_{max} for each transect are calculated from BOUSS-1D runup time series. This analysis consists of an upward zero-crossing analysis to identify individual runup events. Noise near the SWL is eliminated by setting a minimum amplitude and period for runup events equal to 5 and 25 percent of the nearshore wave height and period, respectively. Runup values are sorted in ascending order and percentiles are estimated as $P_i = 100\ (i + 0.5)/n$, where P_i is the i-th percentile and n is the number of runup events. The 98th percentile is linearly interpolated to obtain the 2-percent exceedance level runup. The maximum runup is calculated directly from the time series. Inundation statistics are calculated by determining the location of maximum water level and runup along the transect elevation profile.

5 TWAVE Modeling System

This chapter explains how to use the TWAVE package. The first section describes the functionality of the Excel interface developed for TWAVE. The subsequent sections provide a detailed description of the input and output files.

Excel interface

TWAVE modeling system is implemented in Microsoft Excel®, which serves as the graphical user interface (GUI) for the system's visualization of input and output files. Excel was chosen as an interface because it is available on most personal computers (PCs) and avoids using other proprietary software. The users of TWAVE do not need any commercially available compilers or plotting programs, and once the package is unzipped, it is ready to be used. Separate Excel files are used for individual island applications for easier data management and organization. Each Excel files contains a number of worksheets for different functions. The worksheets are color-coded for easy navigation. Figure 5 shows the first worksheet of the TWAVE package which contains the names and descriptions of worksheets.

Users of TWAVE should familiarize themselves with the Table of Contents and each of the worksheets before attempting to use it in practical applications. The worksheets are arranged sequentially in the order they are utilized and the tab colors are coded based on the worksheet functions. Yellow tabs correspond to worksheets with reference information such as the table of contents and maps. Green tabs represent worksheets used to visualize input. Red tabs are used for worksheets that contain output results in tables and plots. The black tab named STR is the steering worksheet that contains the hyperlinks to run specific TWAVE applications (Figure 6). The applications include pre- and post-processing routines, numerical models, and batch files (*.bat). Batch files are scripts that run several commands and/or executables.

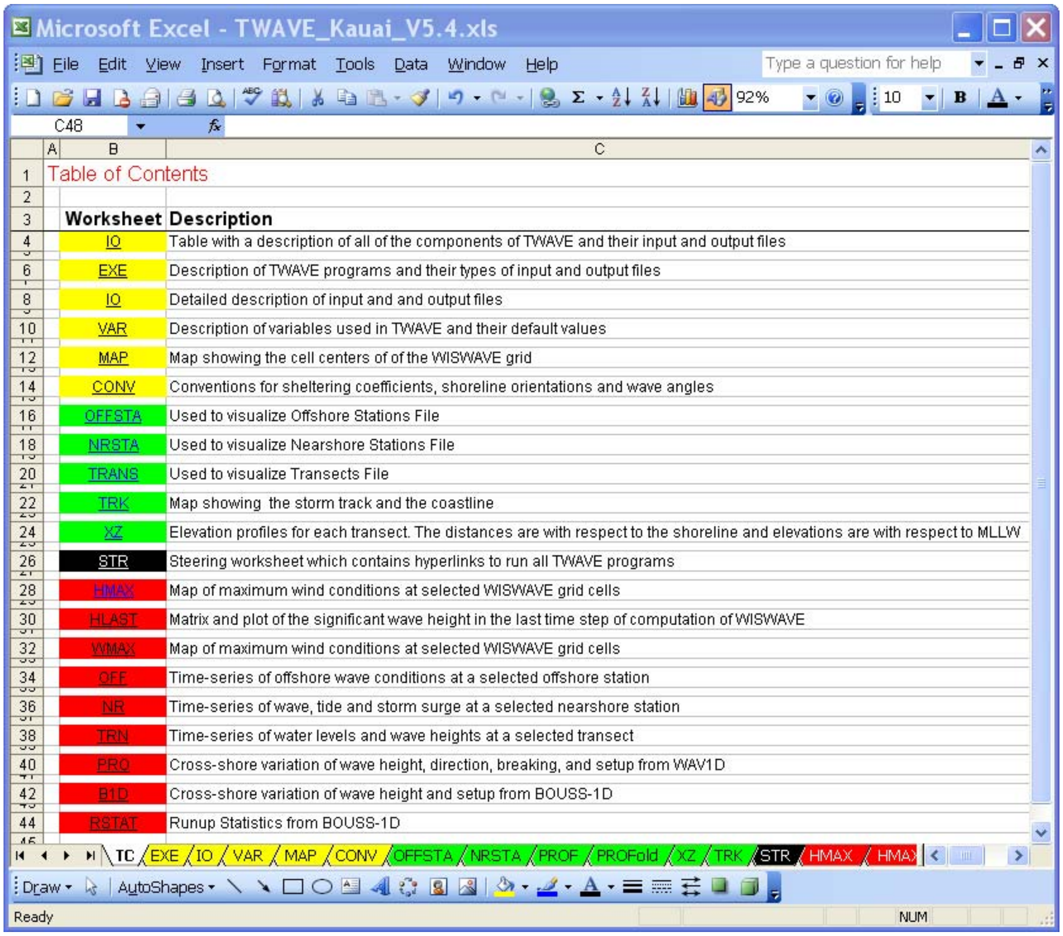


Figure 5. Screen snap shot of first worksheet in TWAVE.

Before executing any models available in the TWAVE, the current path in Excel must be set to the TWAVE work directory. This is done by using the *Open* dialog in Excel which can be accessed by clicking on *File* | *Open* or the using the *Open* button . The current path is set by browsing to the directory /TWAVE/work and then clicking on *Cancel* once the correct path is in the dialog box. If this procedure is repeated, the default path on the *Open* dialog box would be set to /TWAVE/work.

To execute an individual program in the TWAVE, click on the respective box in the Steering worksheet *STR* (Figure 6). This should pop up a DOS window showing the screen output for that program and indicating whether or not the program ran successfully. Once the program is finished, the user should review the screen information, check for any error messages, and press any key to close the window.

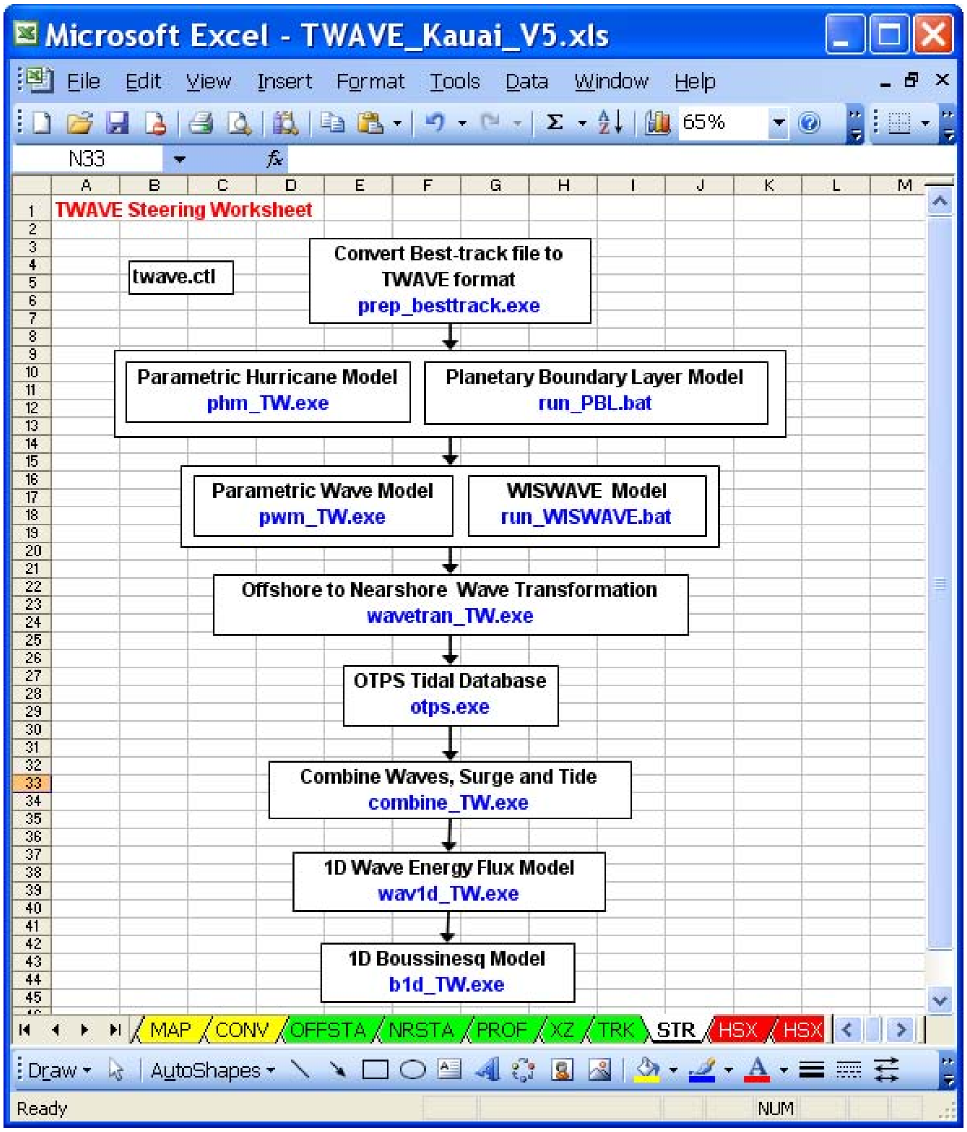


Figure 6. Screen snap shot of steering worksheet (each white box represents a hyperlink).

After running a specific model, the results can be viewed in Excel by updating the external data to be read into specific worksheets from output files. This is done by right-clicking on a cell with external data and clicking on the menu *Data | Refresh Data* or clicking on the Refresh button . Refreshing data will also automatically update the associated plots. Worksheets used to view output files can be used as templates for viewing several files of the same type by copying a worksheet and then replacing the external data file names. A description of the TWAVE programs and their input and output files is provided in Table 1. Some programs such as the wiswave_TW.exe are run with the batch files.

Table 1. TWAVE programs and associated input and output files.

Program	Description	Input	Output
phm_TW.exe	Parametric Hurricane Model	TWAVE Control File Storm Track File	Nearshore Wind and Storm Surge Files
pwm_TW.exe	Parametric Wave Model	TWAVE Control File Storm Track File	Offshore Waves Files
pblinput_TW.exe	Prepares the input files for the PBL model Run within the batch file run_PBL.bat	TWAVE Control File Storm Track File	6-hr Storm Parameters File 1-hr Storm Parameters File
pbl_TW.exe	Planetary Boundary Layer (PBL) model as described in Thompson and Cardone (1996) configured on a WISWAVE grid	TWAVE Control File 6-hr Storm Parameters File 1-hr Storm Parameters File	1-hr Wind and Pressure Fields
wiswave_TW.exe	Spectral wave growth and propagation model as described in Hubertz (1992). The model is run within the batch file run_WISWAVE.bat	TWAVE Control File 1-hr Wind and Pressure Fields WISWAVE Options File	Offshore Station Spectra File Last Significant Wave Height File Maximum Significant Wave Height File
spec_TW.exe	Extracts time series of wind and wave parameters for each WISWAVE observation station (offshore station). Run within the batch file run_WISWAVE.bat	TWAVE Control File Offshore Station Spectra File WISWAVE Options File	Offshore Station Time Series Files
wavetran_TW.exe	Transforms hourly deepwater wave parameters to shallow water to represent near-breaking waves approaching the coast (Jensen 1983; Gravens et al. 1991)	TWAVE Control File Storm Track File Nearshore Station File Offshore Station File Offshore Station Time Series Files	Nearshore Wave Files
wind_inv_bar_TW.exe	Extracts the wind and atmospheric pressure from the PBL model output data and computes the storm surge time series at nearshore stations	TWAVE Control File Storm Track File Nearshore Station Information File 1-hr Wind and Pressure Fields	Nearshore Wind and Storm Surge Files

(Continued)

Key to filename components: *ww* = wis station #, *ssssss* = storm #, *xx* = nearshore station, *ppp* = profile #, *yyyy* = year

Table 1. Concluded.

Program	Description	Input	Output
prep_tide.exe	Prepares the input files for the TPXO tide model	TWAVE Control File Storm Track File Station Information File	Tide Model Setup File Tide Model Lat/Lon/Time File
OTPS.exe	Computes time series of astronomical tides at nearshore stations using the Oregon State Tidal Prediction Software (Egbert and Erofeeva 2002)	Tide Model Setup File Tide Model Lat/Lon/Time File	OTPS Tides File
proc_tide.exe	Converts the OTPS output file to TWAVE format	TWAVE Control File OTPS Tides File	Astronomical Tides File
combine_TW.exe	Prepares the input file for setup_TW.exe by combining the time series of tides, storm surge and wave conditions at nearshore stations	TWAVE Control File Nearshore Station Information File Tide Model Setup File Nearshore Wave Files Nearshore Wind and Storm Surge Files Nearshore Tide File	Nearshore Time-series Files
WAV1D.exe	Computes time series of wave levels, wave ponding, wave setup, runup and inundation at transects along the coast	TWAVE Control File Nearshore Station Information File Profile Information File Nearshore Time-series File Transect Bathymetry Files	Transect Time-series Files Transect Profile Files WAV1D Runup Statistics File run_bouss1d.bat
bouss1d_v3p1exe	1D Boussinesq wave model Run within the batch file run_bouss1d.bat	BOUSS-1D script files Transect Bathymetry Files	BOUSS-1D Transect Files BOUSS-1D Runup time series
proc_ts.exe	Calculates the runup statistics from BOUSS-1D results	BOUSS-1D Runup time series	BOUSS-1D Runup Statistics File
Key to filename components: *ww* = WIS station #, *ssssss* = storm #, *xx* = nearshore station, *ppp* = profile #, *yyyy* = year.			

Input files

Input parameters for different models used inside TWAVE must be specified in separate ASCII files. Input files include the storm track, maximum sustained wind speed, location of nearshore stations, and cross-shore bathymetry profiles. Each input file name is associated with a variable. Table 2 contains the TWAVE input files names, file description, file location, and corresponding variable name. Input file names must be specified within the *Control File* next to the corresponding variable names. An example of the *Control File* is provided in the next section. All input data to TWAVE are in SI units, except the wind speed must be specified in knots.

Table 2. TWAVE default input files.

File(s)	Description	Name	Folder	TWAVE Variable
Control File	Files used to input file names and parameters in TWAVE	twave.ctl	input	NA
Best Track File	Best Track File issued by the Joint Typhoon Warning Center	NA	best_track	*fpred*
Storm Track File	Input file for the PBL model which contains the storm track and maximum wind speed	track_ssssss_NAME.txt	work	*ftrack*
Offshore Stations File	Contains the location and depth of the offshore stations	offsta_info.inp	input	*foffsta*
Nearshore Stations File	Contains the coordinates of the nearshore stations and sets various parameters related to them	nrsta_info.inp	input	*fnrsta*
Transects File	Contains the location and orientation of nearshore bathymetry profiles and sets various parameters related to them	transects.inp	input	*ftrans*
WISWAVE Options File	Contains the settings for the WISWAVE model	options_wiswave.dat	input	*fwisopt*
BOUSS-1D Script Files	Contain BOUSS-1D setup information and post-processing commands	P*ppp*_ssssss.gbat	Bouss1D	*NA*
ssssss= storm ID, NAME = storm name (optional), *ppp* = transect ID number, NA = not applicable.				

Control File

The *Control File* defines all input variables for TWAVE. It includes file names and empirical constants for various numerical models imbedded in TWAVE. The name of the *Control File* is twave.ctl and this name cannot be changed. An example twave.ctl file is shown below.

```
TWAVE Control File
Version 1.0

START_CTL

!For Kauai
ftrack  track_199210.txt    !Storm Track File
foffsta offsta_kauai.inp    !Offshore Station Information File
fnrsta  nrsta_kauai.inp     !Nearshore Station Information File
fprof   profiles_kauai.inp  !Profile Information File
fwisopt  options_kauai.dat  !WISWAVE options file
region  hawaii    !specifies which region to run
fwind  wind.dat   !Wind File
windmodel  0      !0-Holland, 3-Rankine
tidemodel  haw    !OTIS tidal solution

END_CTL
```

The list of the possible variables that may be used in the *Control File* is provided in the Excel worksheet labeled as *VAR*. Each variable must be entered in a separate line within the section between the START_CTL and END_CTL by specifying the variable name followed by its value or file name. Metadata information (e.g., version, project name, etc.) may be specified anywhere by placing an exclamation sign in front of the text. Table 3 shows the complete list of variables that may be specified in the *Control File*. Table 4 provides different run options available in TWAVE.

The *Control File* may be directly edited with Excel by clicking on its hyperlink in the steering worksheet *STR*. Use a default program to open files with the same extension for the hyperlink to work properly. If the file does not open when clicking on the hyperlink, go to Windows Explorer, right-click on the file, click on properties and then select a text editor as the default program (e.g., Wordpad).

Table 3. List of variables for TWAVE Control File.

Name	Description	Default File Name or Value
ftrack	Storm Track File name	NA
fpred	Name of Best Track File	NA
asave	Date and time at which a warm start file is saved as yyyymmddhh	none
aread	Date and time at which a warm start file is read as yyyymmddhh	none
fsnaps	Name of intermediate storm data file at 6-hr intervals	snaps.data
fhisto	Name of intermediate storm data file at 1-hr intervals	histo.data
fwind	Name of storm wind and pressure file	wind.dat
fwmax	Maximum wind field	Wmax.dat
fwisopt	Name of WISWAVE options file	options_wiswave.dat
foffsta	Name of Offshore Station Information File	offsta_info.inp
fnrsta	Name of Nearshore Station Information File	nrsta_info.inp
fprof	Name of Profile Information File	profiles.inp
fhsmax	Maximum significant wave height at every grid point	Hs_max.dat
fhslast	Significant wave height at every grid point at last computation time step	Hs_last.dat
ftidesetup	Tide Model Setup File	tides_setup.inp
ftide	Name of file containing a time series of the tide	tide_otis.dat
flatlontime	Tide Model Lat/Lon/Time File	latlontime.txt
pa	Atmospheric pressure in mbar	1010.0
Ka	Conversion factor between 1-min to 10-min winds	0.87
Km	Conversion factor between PHM winds and 10-m reference height winds	0.8
reefbeg	Threshold depth above which a reef can appear (feet, MSL)	-2
gammab	Ratio of H_s to water depth over the reef	0.6
gamma	Non-dimensional stable RMS wave height	0.4
dx	Spatial resolution of WAV1D	0.5
fric	Runup reduction factor due to non-smooth slope	0.6
B	Wave breaking intensity factor for wave breaking	1
xRankine	Shape factor for modified Rankine vortex wind model	0.5
ksr	Nikuradse roughness factor for reef	0.16
kappa	Empirical wave decay coefficient for wave breaking	0.15

Table 4. TWAVE run options.

Name	Description	Possible Values*	Default
region	Specifies which region to run	Hawaii or Guam	Hawaii
windmodel	Toggle for selecting a parametric wind model	0 – Holland model 3 – Modified Rankine vortex	0
centrpres	Specifies formulation for central pressure when not given	0 – Koba et al. 1990 1 – Atkinson and Holliday 1985	0
tidemodel	Toggle for selecting OTPS tidal solution	haw – Hawaiian Islands tpxo6.2 – Global solution 6.2 tpxo7.0 – Global solution 7.0	tpxo6.2
Bconst	Toggle for specifying a constant B factor for Holland Model	<0 – Calculated >0 – Constant value	-99
Rmaxconst	Toggle for specifying a constant R_{max}	<0 – Calculated (if R_{max}<0) >0 – Constant value	-99
phm4wis	Toggle for parametric wind models to output WISWAVE wind field*	1 – Yes 0 - No	1
phm4adcirc	Toggle for parametric wind models to output an ADCIRC compatible wind field	1- Yes 0 - No	1
ibreak	Selects the method for estimating the breaking wave height	0 - Komar and Gaughan 1973 1 - Breaking wave height equal nearshore wave height	0
iwave_diss	Selects the method to calculate wave dissipation due to breaking	0 - Dally et al. 1985 1 - Alsina and Baldock 2007	0
iwave_fric	Specifies whether to use wave bottom friction	0 - No, 1 - Yes	1
ir2per	Selects the method for calculating the 2% exceedance runup	0 - Mase 1989 1 - CERC 2 - Hedges and Mase 2004	0
irmax	Selects the method for calculating the maximum runup	0 - Mase 1989 1 - Seelig 1983	0
*PBL model always outputs WISWAVE wind field.			

Storm Track File

The *Storm Track File* in TWAVE provides storm track positions, wind speeds, central pressure, and radius of maximum wind speed at 6-hr intervals. The file name is “track_*ssssss*_*NAME*.txt”, where *ssssss* is a storm identifier number and NAME refers to the name of the tropical storm or hurricane. The name of the storm is optional but the six-digit storm ID is required. The ID convention used in TWAVE is the year followed by the storm event number. This allows users to sort storms in a chronological order in folders for easier data management. The *Storm Track File* must be located in the work subdirectory. The name of the *Storm Track File* is specified in the *Control File* using the variable name *ftrack*. An example of the format of a *Storm Track File* is provided below for Hurricane Iniki (track_199210_INIKI.txt):

```
yyyymmddhh  LatN  LonE  W_knt Pres_mb  Rmax_km
1992090918  13.4  205.7   80     984   14.116
1992091000  13.8  204.5   85     980   14.328
1992091006  14.3  203.1   90     960   14.532
1992091012  14.7  202.2  100     960   14.685
1992091018  15.2  201.4  100     951   14.918
1992091100  15.9  200.7  110     948   15.217
1992091106  16.8  200.2  115     947   15.658
1992091112  18.2  200.0  120     939   16.368
1992091118  19.5  200.0  125     938   17.078
1992091200  21.9  200.29 115     945   18.285
1992091206  23.7  200.6  100     959   19.765
1992091212  25.7  201.0   80     980   21.273
```

The *Storm Track File* must have one header line followed by lines consisting of six columns of data separated by blank spaces. The header line has the names of input variables, with the first column containing the date and time (GMT) specified as yyyymmddhh, where yyyy is the year, mm is the month, dd is the day, and hh is the hour. The latitude and longitude values are specified in the second and third columns in degrees N (north) and E (east), respectively. The forth to sixth columns are the maximum sustained wind speed in knots, central pressure in mbar, and radius of maximum wind speed in km, respectively. If the storm's central pressure or the radius of maximum wind speed is not known, a negative value should be placed in the respective columns, and TWAVE will calculate estimated values of these parameters. The *Storm Track File* may be viewed in Excel using the worksheet *TRK*.

Storm databases

Two storm databases are used in TWAVE. The first storm database is the NOAA tropical storm and hurricane database HURDAT (Landsea 2004) available at (http://www.aoml.noaa.gov/hrd/hurdat/). This storm database covers the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea for the time period from June 1851 to December 2007. The second database from the Joint Typhoon Warning Center (JTWC), Naval Pacific Meteorology and Oceanography Center, is the western North Pacific Ocean database (https://metocph.nmci.navy.mil/jtwc/best_tracks/). The HURDAT database is provided in TWAVE format as *Storm Track Files* located in the TWAVE subdirectory data\HURDAT. The JTWC database is provided in its original format as best track files located in the TWAVE subdirectory data\JTWC. The JTWC best track files can be converted to TWAVE *Storm Track Files* by using the *prep_besttrack_TW.exe* utility available in the steering worksheet. The *Best Track files* should be placed in the subfolder named best_track, and their names specified in the *Control File* using the variable name *fpred*.

WISWAVE Options File

This file contains the input settings for the WISWAVE model. The file includes WISWAVE setup information, including frequency bins, number of directional bins, and information about grid cells that are land or water. The file should be located in the *input* folder. The default file name is *options_wiswave.dat* and may be changed using the TWAVE variable *fwisopt*. For additional information about this file, the user is referred to the WISWAVE manual (Hubertz 1992).

Offshore Stations File

The wave estimates from the deepwater wave models are saved at the user-specified *Offshore Stations File*. These wave conditions can be transformed to shallow water for nearshore wave estimates. For additional information, see the section Deep- to Shallow-Water Wave Transformation. The locations and depths of *Offshore Stations* are specified in the *Offshore Stations File*. This file must be located in the *input* folder and the name of the file is specified in the *Control File* using the variable *foffsta*. An example of the default *Offshore Stations File* for the island of Kauai, HI (*offsta_kauai.inp*), is shown below:

```
OffSta LatOff  LonOff  DepOff
G01    22.083  200.167  -999
G02    22.000  200.167  -999
G03    21.917  200.167  -999
G04    21.917  200.250  -999
G05    21.917  200.333  -999
G06    21.833  200.333  -999
G07    21.833  200.417  -999
G08    21.833  200.500  -999
G09    21.833  200.583  -999
G10    21.833  200.667  -999
```

The wave estimates at user-specified *Offshore Stations File* are interpolated from the WISWAVE grid solution file using the nearest neighbor interpolation method. The offshore depths should be indicated as positive depths or as -999 for default deepwater stations. The *Offshore Stations File* may be viewed in Excel using the worksheet named *OFFSTA*.

Nearshore Stations File

Hourly estimates of storm surge, tides, wind, wave heights, wave periods, and wave directions (wave conditions optional) are output at user-specified nearshore stations. These stations can also be used to output water levels at buoy locations located in shallow water or stations within harbors where water elevations are desired but wave heights are not. In the *Nearshore Stations File*, the user may specify an offshore station *Offsta* or N/A for "Not Available" indicating nearshore wave transformation is not necessary. In the first case, the waves will be transformed from the specified offshore station to shallow water using WAVETRAN (Jensen 1983; Gravens et al. 1991).

If no offshore stations are specified, wave heights are set to zero and the *Nearshore Stations File* will output the water level only. The N/A should be used as a placeholder for no offshore stations. The file should be saved in the *input* folder. For visualization purposes, the information in this file may be copied to the Excel worksheet labeled as *NRSTA*. The default name of the input *Nearshore Stations File* (*nrsta_info.inp*) can be changed in the TWAVE *Control File* using the variable name *fnrsta*. An example of this file is shown below for the island of Kauai:

```
NrSta  LatN    LonE     DepNr OffSta Opt AngBath KSH  KSH1 KSH2
I30   21.8990 200.4058  3      NA    1     5     0     0     0
I03   21.8855 200.4396  32     G07   1     20    0     0     0
I28   21.8777 200.4594  35     G08   1     20    0     0     0
I27   21.8754 200.5049  36     G08   1     10    0     0     0
I01   21.8662 200.5413  29     G08   1     10    0     0     0
I29   21.8698 200.5786  32     G09   1     330   0     0     0
I31   21.9520 200.6557  10     NA    1     315   0     0     0
```

where *NrSta* is the name, *DepNr* the water depth, *LatN* the latitude in degrees North, and *LonE* the longitude in degrees east of the nearshore station. *OffSta* is the name of offshore station (e.g., WISWAVE output grid point). The variable *Opt* is used to define the input wave parameters for WAVETRAN. Table 5 shows the options for the parameter *Opt* and

Table 5. Options for input wave parameters for WAVETRAN.

Opt	Wave Parameters
1	Hs, Tp, Dirp
2	Hs, Tp, Dirm
3	Hs, Tm, Dirp
4	Hs, Tm, Dirm

corresponding wave input parameters that must be specified. The subscripts s, p, and m in Table 5 refer to the significant, peak, and mean wave parameters, respectively.

The orientation of offshore bathymetric contours is specified with the angle *AngBath* (slope angle), defined as the angle of the up-slope direction of the bathymetry measured counterclockwise from North. This is illustrated in Figure 7.

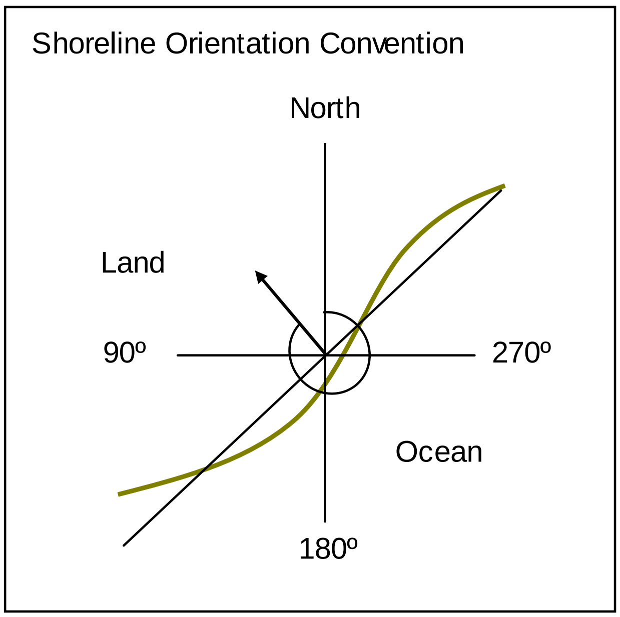


Figure 7. Definition of *AngBath* parameter for offshore bathymetry orientation.

The variable *KSHN* is used to define wave directions that are sheltered by islands or protruding land masses, where the last digit may assume values of N = 0, 1, 2. Therefore, *KSH0* = 0 is for no sheltering, 1 for one-sided sheltering, and 2 for two-sided sheltering. KSH1 defines the sheltered angles to an observer's left when facing offshore. KSH2 defines the sheltered angles to an observer's right, both with respect to the shoreline orientation. Table 6 shows the sheltering values of KSHN for different sheltering angles. The wave angles used for sheltering are specified with respect to the coastline. Figure 8 shows an illustration of the wave angle convention for wave sheltering.

Table 6. Wave sheltering options.

Sheltering Angle Specification			
Sheltering Option (KSH)	1-Sided Sheltering Key (KSH1)	2-Sided Sheltering Key (KSH1)	Sheltered Wave Angle (deg)
0	0	0	None
1	1	0	0 - 10
1	2	0	0 - 20
1	3	0	0 - 30
1	4	0	0 - 40
1	5	0	0 - 50
1	6	0	0 - 60
1	7	0	0 - 70
1	8	0	0 - 80
1	9	0	0 - 90
1	10	0	80 - 180
1	11	0	90 - 180
1	12	0	100 - 180
1	13	0	110 - 180
1	14	0	120 - 180
1	15	0	130 - 180
1	16	0	140 - 180
1	17	0	150 - 180
1	18	0	160 - 180
1	19	0	170 - 180
2	1 - 9	10	KSH1 value + 80 - 180
2	1 - 9	11	KSH1 value + 90 - 180
2	1 - 9	12	KSH1 value + 100 - 180
2	1 - 9	13	KSH1 value + 110 - 180
2	1 - 9	14	KSH1 value +120 - 180
2	1 - 9	15	KSH1 value + 130 - 180
2	1 - 9	16	KSH1 value + 140 - 180
2	1 - 9	17	KSH1 value + 150 - 180
2	1 - 9	18	KSH1 value +160 - 180
2	1 - 9	19	KSH1 value + 170 - 180

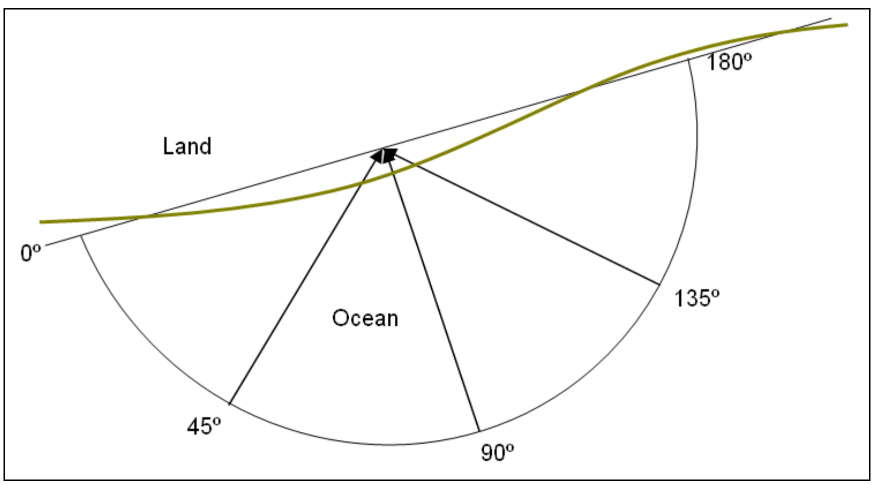


Figure 8. Wave angle convention for wave sheltering.

Transects file

The wave transformation and calculation of ponding levels over reefs and runup require the specification of the following parameters: shoreline orientation (*AngSho*), water depth over the reef (*DepRf*), width of the reef (*WthRf*), diffraction coefficient (*Diff*), roughness factor (*Rough*) for runup calculations, and a factor that accounts for the berm effects (*Berm*). The default values of *Diff*, *Rough*, and *Berm* are 1. The convention for the shoreline orientation is the same as for the offshore bathymetric contours (Figure 7). Guidance on estimates of the roughness factor and the berm factors is available in the *Coastal Engineering Manual* (HQUSACE 2006) Sections VI-5-2-a and 5-3-a. The wave conditions for nearshore wave transformation and selected transects are specified with the variable *StaNr*. An example of the *Profile Information File* is provided next.

```
Profile AngSho  StaNr   WthRf DepRf Slope Diff Rough  Berm
P030     5.0      I30   0      0     0     1     1     1
P003     11.0     I03   0      0     0     1     1     1
P028     7.0      I28   0      0     0     1     1     1
P027     5.0      I27   0      0     0     1     1     1
P001     15.0     I01   0      0     0     1     1     1
P029     328.0    I29   0      0     0     1     1     1
```

The *Profile Information File* should be located in the *input* folder of TWAVE. Similar to *the Station Information File*, the *Transect File* is also saved in the Excel worksheet (labeled with the variable *PROF*) for reference and visualization purposes. TWAVE programs cannot read the input data from the Excel worksheets, and data for these programs must be entered in the corresponding ASCII files.

Transects bathymetry

The bathymetry (topography) for each transect is specified in the *Profile Information File* using a prefix and file extension *.xy. The file has two data columns, and the user-specified distances are in the first column, and elevations are in the second column. Distances are positive in the offshore direction as measured from the position of the MSL at shoreline. Elevations are measured with respect to MSL (below the MSL values are negative). These files should be placed in the folder named *Bouss1D*.

It is not necessary for the points to be spaced at any regular interval because numerical wave models interpolate transect bathymetry from these files. If bathymetric profile data for a new transect needs to be generated from raw LIDAR database, it may be necessary to apply smoothing to the extracted profile as sharp discontinuities in the transect bathymetry can cause instabilities in the nearshore wave transformation models.

BOUSS-1D input files

As mentioned in Chapter 4, BOUSS-1D is run for each transect using the values of nearshore wave height, wave period, and water level at the times of maximum runup as calculated by WAV1D. It was noted in Chapter 4 that it is unnecessary to run BOUSS-1D at hourly intervals. Once the time periods of maximum runup are determined from WAV1D results, BOUSS-1D should be run for each transect at these times with the wave height, period, and water levels calculated by WAV1D.

BOUSS-1D is a refined, physics-based advanced wave model and should be run when the maximum runup is reached. The time of maximum probable runup is determined by running WAV1D. For each transect, WAV1D saves the wave parameters corresponding to maximum probable runup in a batch file named as xxx.bat. This batch file is accessed directly by BOUSS-1D through a setup file. The BOUSS-1D setup file is the only input file for that model. It contains model run parameters, post-processing tools to convert model binary output files to ASCII files, and tools for calculation of wave runup statistics. Each transect has its own setup file named as P*ppp*_setup.gbat, where *ppp* is the transect ID number. An example of the BOUSS-1D script file is shown below.

```
(1) #BOUSS1D_v3p0
(2) 2        # bathymetry input option (1-2) [1]
(3) %1       # name of bathymetry file [.xy]
(4) %2       # storm surge/tidal offset (m) [0.0]
(5) 0.5      # grid spacing for numerical computations (m)
(6) -520.0   # x location of wave generation boundary
(7) 2        # type of wave (1-2)
(8)          # time series synthesis option (1-2) [1]
(9)          # incident wave spectra option (1-2) [1]
(10)         # type of wave spectrum (1-5) [1]
(11)         # JONSWAP spectrum option (1-2) [1]
(12) %3      # peak wave period (s)
(13) %4      # significant wave height (m)
(14)         # spectral peakedness parameter gamma [3.3]
(15) %3*0.6  # minimum wave period
(16)         # maximum wave period (s) [25.0]
(17)         # Rescale truncated spectrum (y/n)? [Yes]:
(18) 300*%3  # duration of synthesized time series
(19)         # time step (s)
(20)         # duration of numerical simulation (s)
(21) 2.0     # turbulent length scale (m) [0.09]
(22) 20      # Chezy bottom friction factor (10-1000)
(23) 0.1     # Smagorinsky constant [0.2]
(24) 50      # width of left end damping layer (m)
(25)         # damping coefficient for left end damping layer (0-1) [1]
(26)         # width of right end damping layer (m) [0.0]
(27) 0       # damping value for right end damping layer (0-1) [1]
(28)         # number of instants of time for surface elevation output [0]
(29)         # number of spatial locations for time series output [0]
(30)         # Create an animation of the surface elevation? [No]:
(31) %1      # prefix for output files
(32) #END
(33) #EXPORT2
(34) %1_%5_xHsMWL.dat # name of ASCII output file [.DAT]
(35) 2            # Implicit Variable Option [1]
(36) 2            # number of GEDAP input files (1-20) [1]
(37) %1_hs        # name of GEDAP input file no. 1 [.001]
(38) %1_mwl       # name of GEDAP input file no. 1 [.001]
(39) #END
(40) #EXPORT2
(41) runup_ts.dat # name of ASCII output file [.DAT]
(42) 2            # Implicit Variable Option [1]
```

The first column (with the line numbers in parentheses) is shown here only for describing the lines, but this column does not exist in the setup file used by the model. Values preceded by a percent sign are input parameters that are passed into BOUSS-1D model from the batch file run bouss1d.bat. This batch file is written by the WAV1D model and the user does not need to revise the file. The variables passed to BOUSS-1D from the batch file are: name of the bathymetry file (line 3), transect label (P*ppp*, line 31), water level (line 4), peak wave period (line 12), significant wave height (line 13), and storm ID.

Lines 2 through 31 are the input parameters for BOUSS-1D. The pound sign (#) in front of a program name signifies executing that code. The BOUSS-1D model input parameters specified on each line with a preceding pound sign (#) are user comments or recommended default values. A brief description of input parameters is provided on each line following the pound sign. If no value exists, than the default value is used as indicated by the values in the square brackets.

The values of significant wave height and mean water level for each transect are written in lines 33 through 38. These values are written in a file named P*ppp*_*ssssss*_xHsMWL.dat, where *ppp* is transect ID and *ssssss* storm ID. Lines 39 through 43 are saved in a file named runup_ts.dat that contains wave runup time series. Line 44 executes the Fortran code that calculates wave runup statistics. For additional information, see the Direct Calculation of Wave Runup section from BOUSS-1D Results. When setting up a new transect, it is recommended to run BOUSS-1D interactively. This is done by typing the executable code name in a DOS window. The interactive run allows the user to physically see the values of various parameters as calculated by BOUSS-1D pre-processor. The interactive run ensures model settings are correct, including the location of wavemaker, width of the damping layers, etc. For additional information concerning input to Boussinesq model, users may consult available publications (Demirbilek et al. 2005a and b; Demirbilek et al. 2007; Demirbilek and Nwogu 2007; Demirbilek et al. 2008). Because BOUSS-1D is expected to be used for many transects (tens to hundreds of transects), a single batch file called run_bouss.bat may be used to run BOUSS-1D for all transects at once. The batch file allows for quick turn-around times and easier editing of I/O files.

TWAVE output files

TWAVE results can be viewed and plotted using Microsoft Excel. This eliminates the need of using other external plotting software. Output files are imported to Excel by refreshing the external data read by worksheets and selecting the appropriate resource files. The data used by a worksheet and plots are also automatically updated. Table 7 provides a description of all TWAVE output files, including the file names, format, location (directory), and associated variables.

Table 7. TWAVE output file names, format, location, and corresponding TWAVE variables.

File(s)	Description	Default Name or Format	Location	TWAVE Variable
Last Significant Wave Height File	Contains a matrix of the significant wave height from the last time step of WISWAVE simulation	Hs_last.dat	.\offshore\	*fhslast*
Maximum Significant Wave Height File	Contains a matrix of the maximum significant wave height during the WISWAVE simulation	Hs_max.dat	.\offshore\	*fhsmax*
Maximum Wind File	Contains a matrix of the maximum wind during the wind model simulation	Wmax.dat	.\wind_fields\	*fwmax*
Warm Start File	Files saved and read by WISWAVE to start a new simulation at an intermediate point in time	ssssss*mmddhh*.wrm	.\offshore\	NA
Offshore Station Time Series Files	Contains a time series of wave and wind conditions at the offshore stations	G*ww*_ssssss.off	.\offshore\	NA
Nearshore Waves File	Contains a time series of wave conditions at individual nearshore stations	I*xx*_ssssss.PH3	.\nearshore\	NA
Nearshore Wind and Storm Surge Files	Contains a time series of wind, atmospheric pressure and storm surge at individual nearshore stations	I*xx*_ssssss.uvs	.\nearshore\	NA
Nearshore Astronomical Tides File	Contains a time series of astronomical tides at individual nearshore stations	I*xx*_ssssss.ast	.\nearshore\	NA
Nearshore Station Time Series	Contains a time-series of the waves, wind, storm surge and tide at nearshore stations	I*xx*_ssssss.wts	.\nearshore\	NA
Transect Time series Files	Contains a time-series of the wave setup, runup and inundation at transects	P*ppp*_ssssss.wsr	.\transects\	NA
Transect Profile	Contains a profile of the wave heights and water levels along each transect for the time period of maximum water levels	P*ppp_ssssss_max.dat*	.\transects\	NA
WAV1D Runup Statistics File	Contains the runup statistics calculated by WAV1D at individual transects	Rstat_W1D_ssssss.dat	.\transects\	NA
BOUSS-1D Transect File	Contains the cross-shore variation of significant wave height and setup (mean water level)	P*ppp*_ssssss_xHsmwl.dat	.\Bouss1D\	NA
BOUSS-1D Runup Statistics File	Contains the BOUSS-1D runup statistics for all profiles	Rstat_B1D_ssssss.dat	.\Bouss1D\	NA
Format Key: ssssss - storm ID, mm - month, *dd* - day, *hh* - hour, *ww* - offshore station ID, *xx* - nearshore station ID, and *ppp* - transect ID.				

Deepwater wave and wind fields

The WISWAVE model calculates values of the maximum significant wave height ($H_{s,max}$) and significant wave height at the last time step ($H_{s,last}$) at every grid cell. These results are saved as matrices in separate ASCII files in the folder named *offshore*. The default names of these output files are *Hs_max.dat* and *Hs_last.dat,* respectively. These can be changed in the *Control File* using the variables *fhslast* and *fhsmax,* respectively. The grid cells along the boundaries and cells corresponding to land are assigned a value of zero in the files. $H_{s,max}$ and $H_{s,last}$ are imported to the worksheets labeled *HMAX* and *HLAST,* respectively. The PBL wind model also outputs the maximum wind speed at every grid cell during the simulation. This file is saved in the folder named *wind_fields*, and the default file name *Wmax.dat* can be changed in the *Control File* using the variable *fwmax*. The maximum wind speed grid can be imported and viewed in Excel using the worksheet labeled as *WMAX*. The format for all of these files is shown next, where X represents wave heights or wind speed and the number in parenthesis are the values of cell (I,J):

```
X(1,1) X(2,1) X(3,1) X(4,1)  …   X(n,1)
X(1,2) X(2,2) X(3,2) X(4,2)  …   X(n,2)
X(1,3) X(2,3) X(3,3) X(4,3)  …   X(n,3)
X(1,4) X(2,4) X(3,4) X(4,4)  …   X(n,4)
   :      :      :      :           :
X(1,m) X(2,m) X(3,m) X(4,m)  …   X(n,m)
```

Offshore stations time series

This file contains wave information at offshore stations that will be transformed to nearshore. The files contain values of the wave heights, wave period, and wave directions. The specific format and variables will depend on whether the WISWAVE or parametric wave model is run. If WISWAVE is run, the post-processing subroutine *spec_TW.exe* reads the WISWAVE output file and writes a separate output file for each offshore station. If the parametric wave model is run, these files are used, but they will not contain wind information. These files are saved in the folder *offshore* and the file names are G*ww*_*ssssss*.off, where *ww* is the offshore station identification number and *ssssss* is the storm identification number. An example of this file type for Hurricane Iniki is provided next.

```
199210 G26
yyyymmddhh  Hmo Tp Drp Tm Drm  W  Dir
1992090919  0.2  4   0  4 270  7  65
1992090920  0.4  4  54  4 281  7  65
1992090921  0.5  4  65  4  65  7  65
1992090922  0.6  4  65  4  65  7  65
1992090923  0.7  4  65  4  65  8  65
1992091000  0.8  4  65  4  65  8  65
```

where H_{mo} = zeroth moment wave height (m), T_p = peak period (sec), D_{rp} = peak wave direction (degrees clockwise from North), T_m = mean wave period, D_{rm} = mean wave direction (degrees clockwise from North), W = wind speed (m/sec), and *Dir* = wind direction (degrees clockwise from North). The first line indicates the storm ID followed by the *Offshore Station ID*. The second line of the file is a header line. These files are imported to the Excel using the worksheet labeled *OFF*.

Nearshore waves files

These files contain values of hourly significant wave height, wave period, and wave direction at nearshore stations starting at the first hour and ending at last hour of the *Storm Track File*, respectively. These are output by WAVETRAN_TW.exe model that performs wave transformation from deep water to shallow water, and read by combine_TW.exe model that combines winds, waves, tides, and storm surge information into a single input file for WAV1D to use. The files are saved in the folder *nearshore* and named as I*xx_ssssss*.PH3, where xx is the nearshore station ID, and *ssssss* is the storm ID. The nearshore wave files are internal files, and users need not be concerned with these files unless they want to use input wave conditions for WAV1D from a different source. In this case, users must provide a file for each nearshore station with the following format:

```
yyyymmddhh         Hs       T    Theta
1992091107        0.6     6.0   131.4
1992091108        0.7     6.0   131.7
1992091109        0.8     6.0   132.0
1992091110        0.9     6.0   132.3
1992091111        0.9     7.0   134.4
1992091112        1.0     7.0   135.0
```

where the first line is the header line, followed by lines containing a 10-digit time stamp, the significant wave height, wave period, and wave direction. Here and in the subsequent sections, unless otherwise noted, T = wave period (sec), *Theta* = wave direction (degrees clockwise from North). Note that the input wave height, period, and direction data may be either the mean or peak values depending on the *opt* value used in the deep to shallow wave transformation (see section in Chapter 4 called Deep- to Shallow-Water Wave Transformation). Wave parameters are input starting 1 hour past the storm track time, and hourly values are required through the end of the storm duration. If the correct time stamp is not entered, combine_TW.exe will give an error message.

Nearshore wind and storm surge files

These files contain hourly wind speed, direction, atmospheric pressure, and storm surge at individual nearshore stations covering the same time period specified in the *Storm Track File*. These files are located in the folder *nearshore* and named as *Ixx_ssssss.uvs*, where *xx* is the nearshore station ID and *ssssss* is the storm ID. These files are internal files written by the wind models and read by combine_TW.exe model to write the Nearshore Stations Time Series files (see the section Nearshore Stations Time Series files for additional information). If the user wants to enter different wind and pressure data from another source (model or database), this is done by writing the Nearshore Wind and Storm Surge Files in the following format:

```
yyyymmddhh    W      Dir   Pres      Surge
1992090918   5.71    22.8  1009.8   0.002
1992090919   5.85    23.9  1009.8   0.002
1992090920   6.04    25.1  1009.8   0.002
1992090921   6.28    26.4  1009.8   0.002
1992090922   6.62    27.8  1009.7   0.003
```

where the first line is the header line that provides name of variables for each column, *Pres* = atmospheric pressure (mbar), *Surge* = storm surge (m), and *W* and *Dir* are defined as in previous sections. The Nearshore Wind and Storm Surge files are internal and output by the wind models and read by combine_TW.exe model.

Nearshore astronomical tide files

These files contain time series of the astronomical tides at each nearshore station at hourly intervals. These data start at the first hour and end at the last hour specified in the *Storm Track File*. The files are named as *Ixx_ssssss.ast* and located in the *nearshore* folder. The program proc_tide.exe converts the OTPS output file to a Nearshore Astronomical Tide File. The program proc_tide.exe is run within the batch script (run_otps.bat), which is executed from the Steering Excel worksheet

(*STR*). The batch file prepares the OTPS input files, runs the OTPS program, and runs the proc_tide.exe code. The file format is provided below to allow users to implement other tidal databases that can be written in the format of TWAVE Astronomical Tide Files. The file format is:

```
yyyymmddhh      Tide
1992090918     -0.248
1992090919     -0.235
1992090920     -0.161
1992090921     -0.040
```

The header line contains the time stamp and the variable name used for astronomical tides. The tides should be in m and referenced to the local MSL.

Nearshore stations time series

The wave conditions, storm surge elevations, and tide elevations calculated from different components of TWAVE are combined into one file by the program *combine_TW.exe*, and these files are saved in the *nearshore* folder. These files are imported to the Excel worksheet labeled *NR*. The format name for these files is *Ixx_ssssss.wts*, where *xx* is the nearshore station ID and *ssssss* is the storm ID. The top section of the Nearshore Station time series file is shown below for reference:

```
199031 I08
yyyymmddhh   H     T    Theta  Tide     W    Dir  Surge
1990121918   1.2  11.0  135.1  -0.468  14.4 181.6  0.105
1990121919   1.2  11.0  136.4  -0.391  14.8 180.4  0.108
1990121920   1.2  11.0  136.4  -0.264  15.3 179.1  0.111
1990121921   1.3  11.0  137.4  -0.112  15.8 177.9  0.115
1990121922   1.4  11.0  137.4   0.038  16.3 176.7  0.119
```

The first line contains the storm ID and nearshore station ID and the second line is a header line. The variable names are defined as in the previous sections.

Transect time series

The reef wave program_TW.exe outputs the time series of wave setup, wave runup, and inundation at each transect to files named as P*ppp_ssssss.wsr*, where *ppp* is the transect identification number, and *ssssss* is the storm ID. The files are saved in the *transects* folder and can be imported to Excel using the *TRN* worksheet. The first line in these files contains the storm ID and the transect ID, and lines 2, 3, 5, and 7 are the header lines.

The lines 8 and beyond contain hourly wave, wind, and water level statistics at the nearshore station and over the reef-top, and runup statistics. The following parameters are output at the deepwater end of transect: wave height, period, direction, wind speed and direction, tide, and storm surge. The following parameters are output over the reef-top: wave height H_r (m), setup *etar* (m), and water depth d_r (m). The 2-percent exceedance runup (*R*2%) is in meters and with respect to the SWL, the 2-percent exceedance water level (*WL2*%) is in meters and with respect to the MSL. The 2-percent exceedance inundation (*I*2%) is in meters with respect to the MSL at the shoreline. These are calculated based on empirical equations described in Chapter 4 using the wave height on the reef top (H_r), the deepwater wave length, and the beach slope.

The same variables as in the hourly time series are output for the highest *WL*% and *R2*%, *and* these are shown on lines 4 and 6, respectively. An example of the *Transect Time Series file* is provided next.

```
199031 P001
yyyymmddhh   Hs    Tp   Theta   W     Dir   Tide   Surge  etar    dr     Hr     R2%    WL2%    I2%
Maximum Water Level Conditions
1990122100  8.60 14.00 142.40 27.80 306.20  0.203  0.232  1.291  1.527  1.046  1.701  3.428  74.08
Maximum Runup Conditions
1990122101  8.10 14.00 147.70 26.10 309.20  0.255  0.211  1.190  1.457  0.996  1.648  3.304  71.18
Time-series
1990122004  3.80 14.00 116.20 21.30 171.30  0.151  0.161  0.793  0.906  0.587  1.173  2.278  45.41
1990122005  4.10 14.00 118.00 22.40 171.40  0.113  0.171  0.843  0.928  0.607  1.198  2.325  46.06
1990122006  4.50 14.00 119.40 23.80 171.70  0.100  0.184  0.896  0.981  0.648  1.249  2.429  47.52
1990122007  4.90 14.00 119.40 25.20 172.30  0.116  0.198  0.940  1.055  0.701  1.314  2.568  50.77
1990122008  5.10 14.00 118.00 26.70 173.00  0.151  0.214  0.952  1.118  0.742  1.364  2.681  53.85
1990122009  5.30 14.00 116.20 28.40 174.40  0.190  0.232  0.962  1.185  0.787  1.416  2.799  57.23
1990122010  4.80 14.00 110.30 30.30 176.40  0.212  0.254  0.879  1.146  0.752  1.375  2.719  54.94
1990122011  4.80 14.00 108.80 32.40 179.30  0.200  0.279  0.873  1.153  0.756  1.379  2.731  55.27
1990122012  5.00 14.00 107.60 34.70 183.80  0.144  0.309  0.903  1.157  0.763  1.388  2.743  55.62
1990122013  5.30 14.00 107.60 37.00 190.30  0.045  0.340  0.958  1.144  0.762  1.387  2.730  55.24
1990122014  5.80 14.00 108.80 39.70 199.70 -0.086  0.377  1.048  1.140  0.770  1.396  2.735  55.38
1990122015  6.80 14.00 110.30 42.00 212.40 -0.226  0.408  1.203  1.186  0.814  1.447  2.832  58.17
1990122016  7.80 14.00 113.20 43.00 228.70 -0.349  0.422  1.360  1.234  0.856  1.495  2.928  60.93
1990122017  8.60 14.00 116.20 42.10 247.30 -0.431  0.411  1.488  1.269  0.886  1.529  2.997  62.88
1990122018  9.10 14.00 119.40 40.60 262.90 -0.455  0.390  1.565  1.301  0.910  1.555  3.055  64.55
1990122019  9.00 14.00 123.30 38.30 275.20 -0.414  0.362  1.547  1.296  0.906  1.551  3.046  64.29
1990122020  9.00 14.00 130.60 35.70 285.90 -0.316  0.330  1.511  1.326  0.925  1.571  3.096  65.73
1990122021  8.90 14.00 136.50 33.70 293.10 -0.180  0.300  1.443  1.364  0.947  1.596  3.159  67.40
```

Transect profile

The variations of wave parameters and water levels along each transect are output for the hour of maximum *WL2%* to files named P*ppp_ssssss*_max.dat, where *ppp* is the transect ID. These files are written to the folder named *transects* and can be imported and viewed in Excel using the worksheet named *PRO*. An example of a Transect Profile File is shown below.

```
199031 P001
yyyymmddhh   Hs    T   Theta   W     Dir   Tide+Surge
1990122100  8.60 14.00 142.40 27.80 306.20  0.435
     xr     hr    dr      Hr     etar     ar
    62.99  -0.12   1.697  0.9414   1.385   -4.029
    R2%    Rmax    WL2%   WLmax    I2%     Imax
   1.07    1.28    2.89    3.10  108.39  114.11
  x       h     slope      d       Hs     eta      a       Qb       L        V
-334.01  19.270   0.318  19.265   8.648   -0.005 -17.023   0.091 181.056   0.248
-333.51  19.112   0.318  19.105   8.656   -0.006 -16.961   0.096 180.414   0.256
-333.01  18.953   0.318  18.945   8.664   -0.007 -16.899   0.102 179.768   0.265
-332.51  18.794   0.318  18.785   8.673   -0.009 -16.836   0.108 179.117   0.274
-332.01  18.635   0.318  18.625   8.681   -0.010 -16.773   0.114 178.462   0.283
-331.51  18.476   0.318  18.465   8.689   -0.011 -16.709   0.120 177.802   0.292
```

The storm ID number and transect ID are in the first line. The second line is the header line, and provides names of the nearshore parameters at the hour of maximum *WL2%*. The values of these parameters are given on line three. The forth line is the header line for the reef-top parameters whose values are provided on line five. These parameters are: x_r = cross-shore location where the reef-top is defined (m), h_r = reef-top water depth (m, MSL), d_r = reef-top water depth with respect to SWL, H_r = wave height over the reef-top (m), *etar* = wind and wave setup over the reef-top (m), a_r = reef-top incident wave angle (degrees with respect to shore normal). The sixth line is the header line for the runup statistics, and values of these are shown on line seven. The eighth line is the header line, where *eta* = wave + wind setup, a = incident wave angle, Q_b = breaking index or fraction of broken waves, L = wave length, V = alongshore current speed.

WAV1D Runup Statistics File

Wave runup statistics are calculated in WAV1D using empirical formulas described in the section "Calculation of Wave Runup Statistics, Runup Time Series." The *WAV1D Runup Statistics File* is located in *transect* folder and may be viewed in Excel using the worksheet named *RW1D*. The file contains the transect name and estimates of the maximum and 2-percent exceedance runup, water levels, and inundation limits.

```
Trans   Rmax     R2%    WLmax   WL2%    Imax    I2%
P030    4.81    6.21    6.18    7.59   36.05   44.25
P027    5.96    7.49    6.70    8.23   61.64   65.19
P001    3.32    4.20    4.49    5.37   43.01   46.89
```

BOUSS-1D transect files

The BOUSS-1D transect files contain calculated cross-shore variation of wave heights and setup for each transect. The file names are P*ppp*_*ssssss*_xHsmwl.dat, where *ppp* is transect ID and *ssssss* the storm ID. The files are located in the *Bouss1D* folder and may be imported and viewed in the Excel worksheet *B1D*. These ASCII files contain three columns of data: (1) x-coordinate (m), (2) zero-th moment wave height (m), and (3) total mean water level (MWL) (m). Note the wind setup is added to the entire domain of BOUSS-1D and MWL has the wave setup (e.g., MWL=SWL+wave and wind setup).

BOUSS-1D Runup Statistics File

Runup statistics are calculated from BOUSS-1D runup time series files following the procedure outlined in section “Calculation of Wave Runup Statistics, Runup Time Series.” The BOUSS-1D Runup Statistics File is located in the *Bouss1D* folder and may be imported and viewed in Excel using the worksheet *RB1D*. The file contains the transect name, maximum runup, and estimates of the 50-, 33-, 10-, and 2-percent exceedance level runup. An example BOUSS-1D *Runup Statistics File* is shown next.

```
Trans   Rmax    R2%    WLmax   WL2%    Imax    I2%
P030    4.81    6.21    6.18    7.59   36.05   44.25
P027    5.96    7.49    6.70    8.23   61.64   65.19
P001    3.32    4.20    4.49    5.37   43.01   46.89
```

6 Example Applications

Example 1: Hurricane Iniki (Kauai)

Hurricane Iniki is the most recent hurricane that has made landfall on the Hawaiian Islands and produced significant flooding and wind damage on the island of Kauai. The storm was upgraded to hurricane strength on 9 September 1992 at 12:00 GMT approximately 800 km offshore. It made landfall at approximately 00:00 GMT on 12 September 1992 as a category 4 storm in Saffir-Simpson scale. This hurricane produced maximum winds in excess of 120 knots. Figure 9 shows the storm track for Hurricane Iniki and locations of the National Data Buoy Center (NDBC) buoys in the area.

In the Northern Hemisphere, the strongest winds occur in the forward right quadrate of the hurricane. Thus, the southeast portion of the island received the strongest winds and highest waves. Figure 10 shows the spatial field of maximum winds at each grid cell as computed with the PBL model from hourly values. The curved contours are due to interpolation between the hourly intervals.

Wind and wave data were collected by four buoys (Figure 9). However, buoys 51001 and 51004 are too far from the storm track and could not be used in validation; only buoys 51002 and 51003 were used in the modeling validation. The buoys recorded hourly wind speed and direction for 8.5 min. Wind speeds were converted from the buoy anemometer height of 5 to 10 m using the method of Liu et al. (1979). Significant wave height and mean wave period were also recorded at hourly intervals as 20-min records.

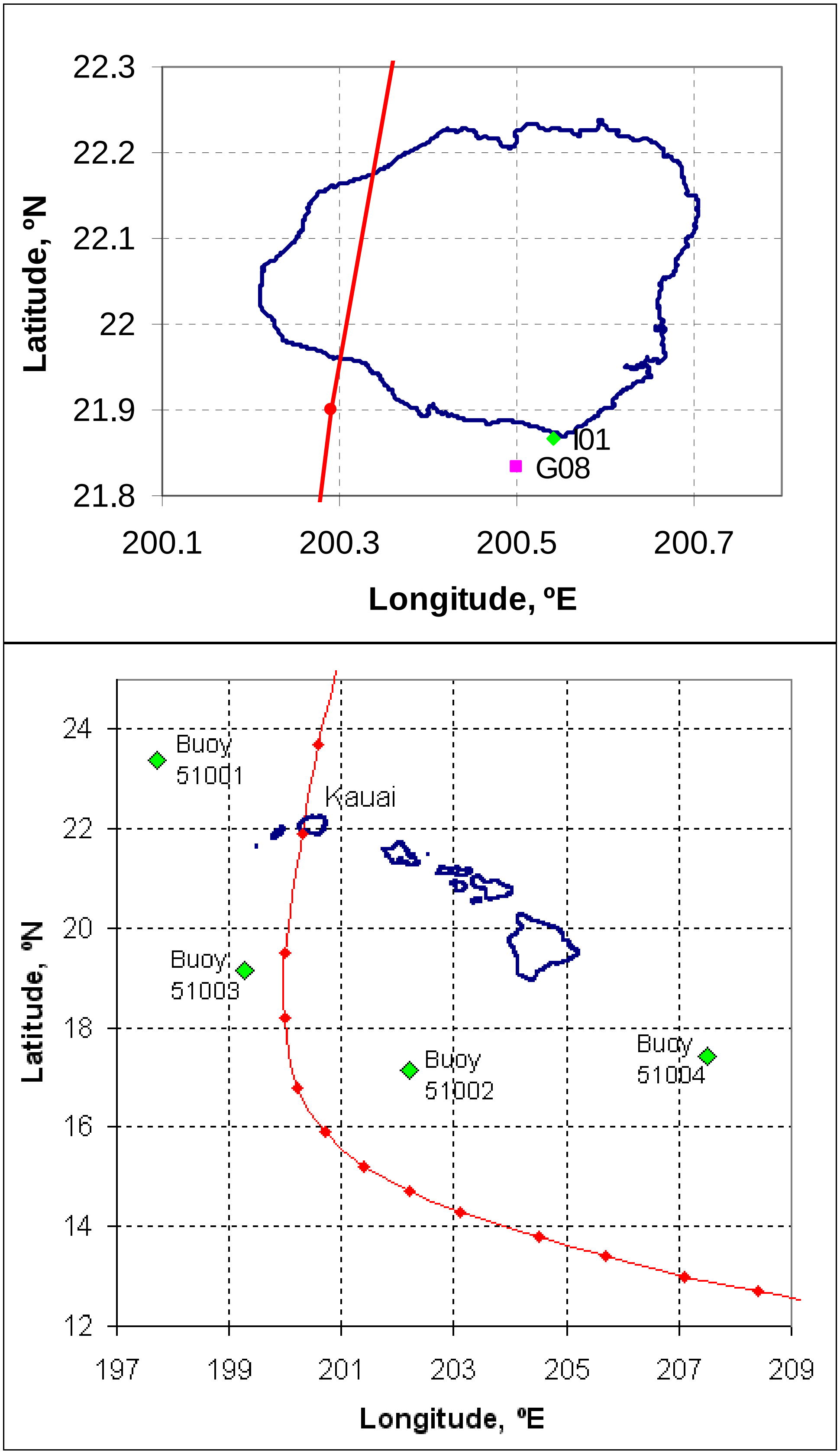


Figure 9. Storm track for Hurricane Iniki.

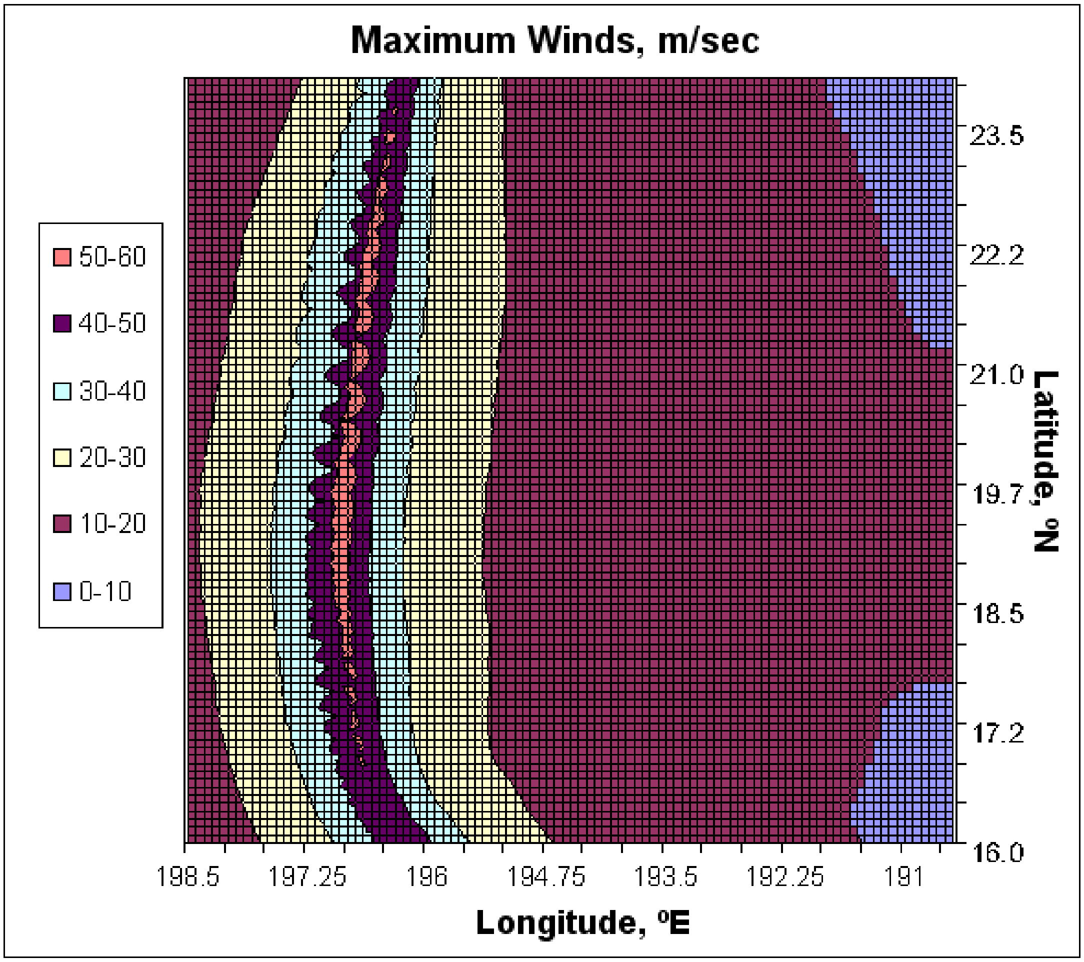


Figure 10. Maximum wind speeds for Hurricane Iniki calculated using PBL model.

Figures 11 and 12 show a comparison of measured and computed wind speeds at buoys 51002 and 51003 using the PBL, Holland, and Modified Rankine Vortex models. The Holland model was run with a scaling parameter of $B = 1.3$, and the shape parameter for the Modified Rankine Vortex model was set to $X = 0.5$.

The storm passed within approximately 250 km to the south of Buoy 51002 and 460 km to the east of Buoy 51003. All three models performed reasonably well compared to measured wind speeds reported by both buoys. The Modified Rankine Vortex and Holland Models produced similar wind speeds at Buoy 51002 and the Holland and PBL models produced similar wind speeds at Buoy 51003. The wind direction for Modified Rankine Vortex and Holland models are identical because they were calculated based on the position of storm relative to the buoys (see Chapter 2 for details).

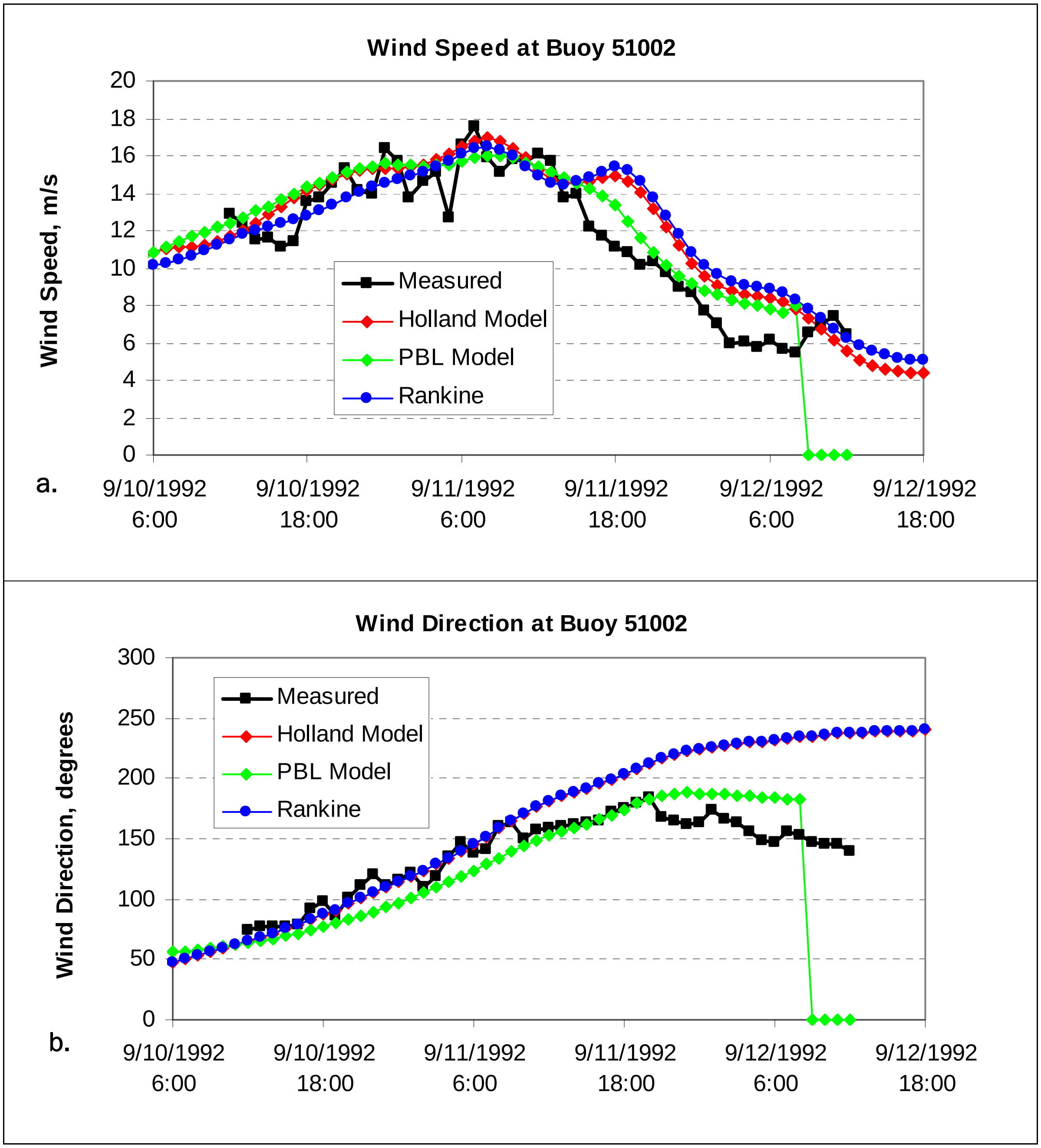


Figure 11. Comparison of (a) wind speed and (b) direction at Buoy 51002 for various wind models.

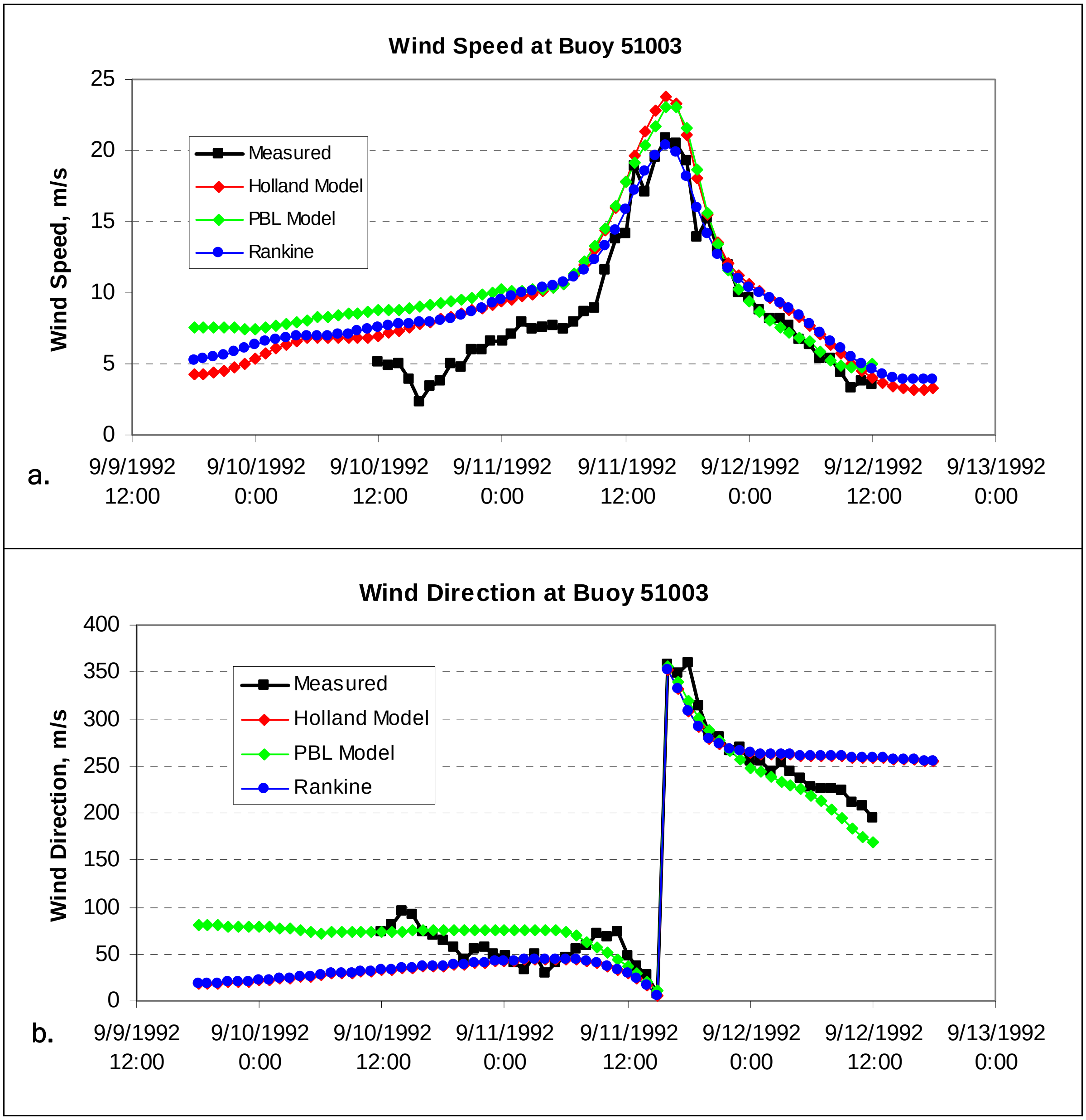


Figure 12. Comparison of (a) wind speed and (b) direction at Buoy 51003 for various wind models.

WISWAVE was run for the Hawaiian Islands with the PBL model winds. The maximum significant wave height for each model grid point is shown in Figure 13. Calculated significant wave heights for Hurricane Iniki from WISWAVE were greater than 15 m about 280 km south of Kauai. Near the south coast of Kauai, significant wave heights reached 13 m, and 9 to 10 m on the east and west coasts.

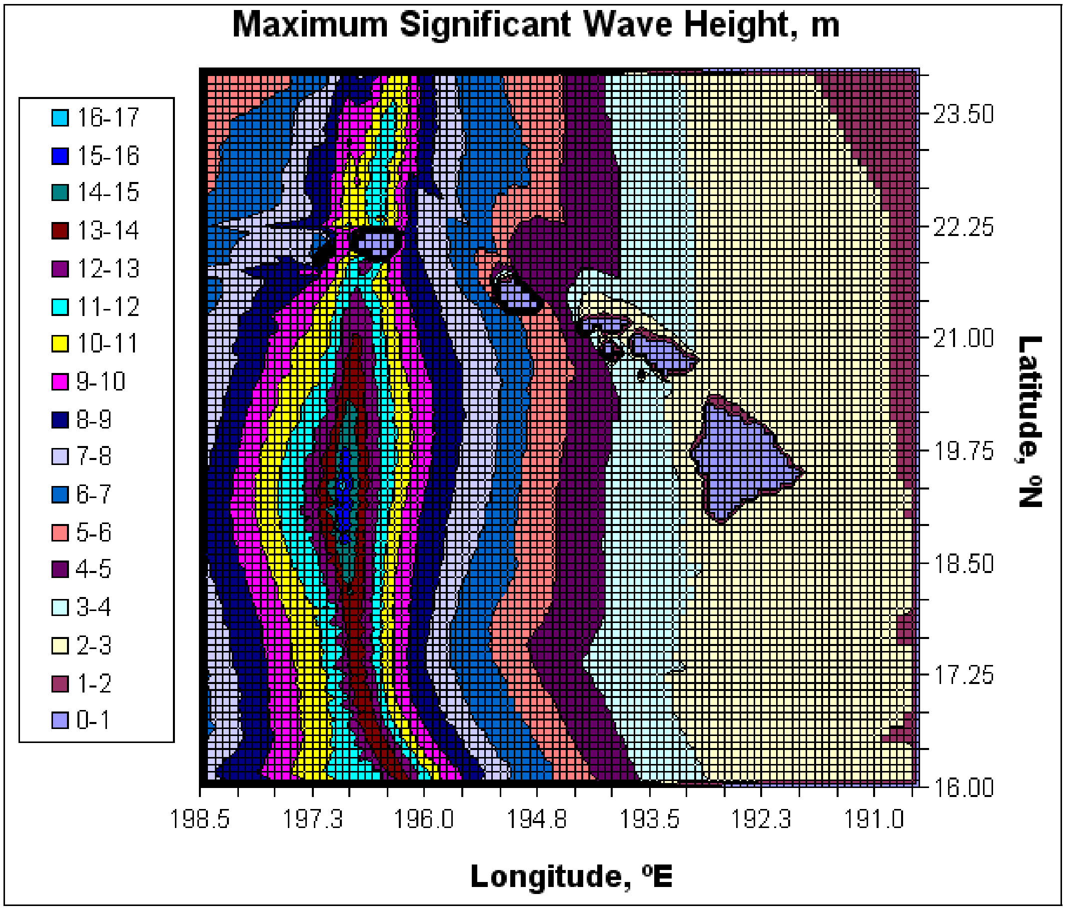


Figure 13. Maximum significant wave heights during Hurricane Iniki calculated using WISWAVE and PBL winds.

The comparison of measured and computed wave heights and periods are shown in Figures 14 and 15. Significant wave height is defined as the zero-moment wave height here. The comparison at Buoy 51002, which was to the right of the forward direction of storm, is good. The computed mean wave periods are also within 2 sec of the measured values. The computed wave heights compare well with measurements. The maximum difference between calculated and measured wave heights is 2m, occurring between 0:00 and 12: 00 GMT on 11 September 1992.

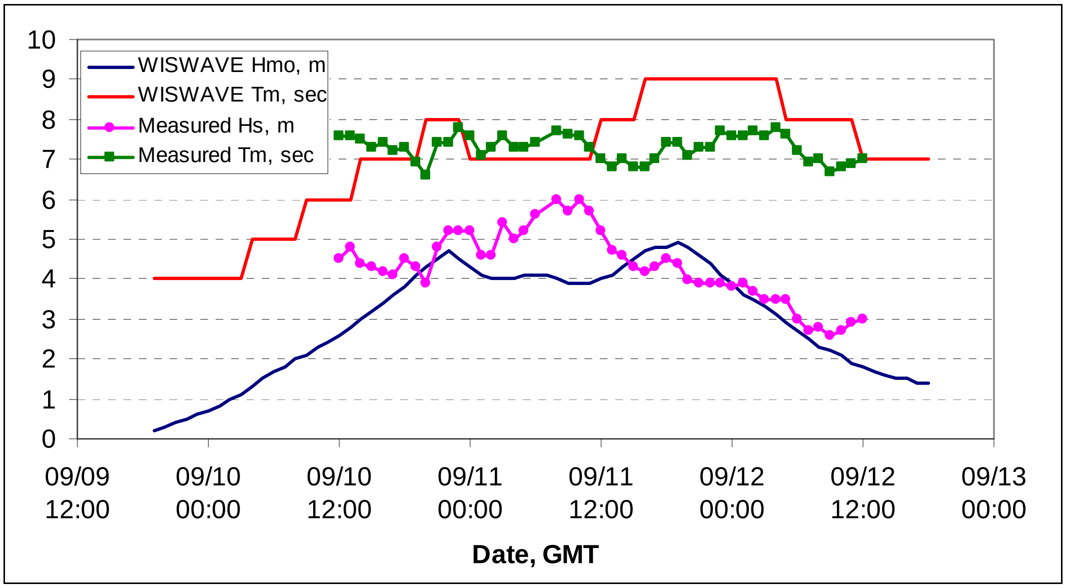


Figure 14. Comparison of significant wave heights and mean wave periods at Buoy 51002 for Hurricane Iniki.

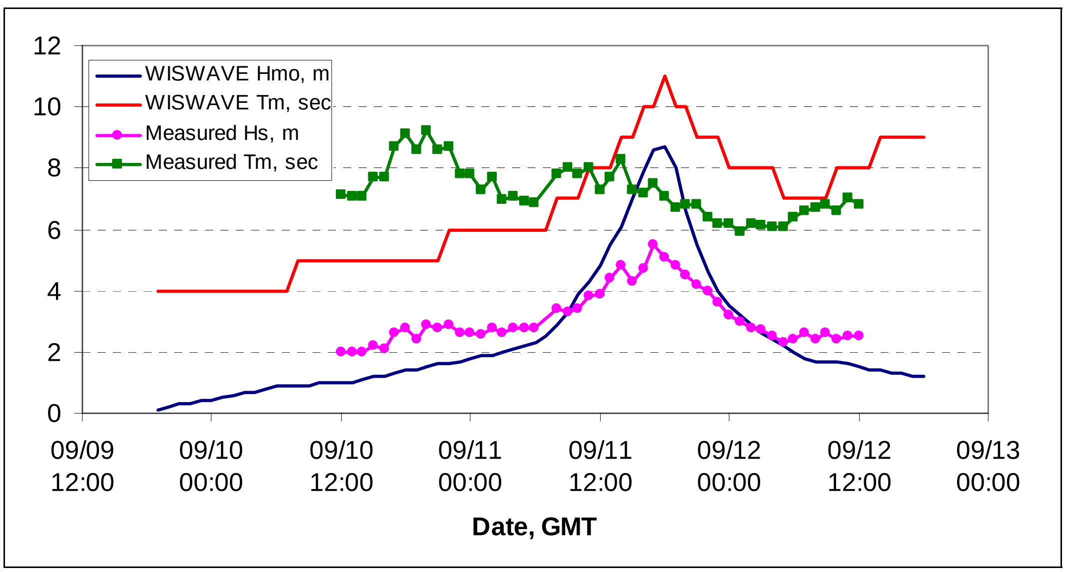


Figure 15. Comparison of significant wave heights and mean wave periods at Buoy 51003 for Hurricane Iniki.

Without calibrating models to data from this storm, a much greater difference occurs between the computed and measured wave heights and wave periods to the right of the storm. The computed wave heights were underestimated by 2m before 10:00 GMT on 11 September, and over estimated by 3m when the storm passed close to the buoy at around 07:00 GMT on 11 September 1992. The mean wave periods have a maximum difference of approximately 4 sec. The under- and over-predicted wave height differences are significant. There was also a phase lag that caused an associated lag in the surge peak. Additional validation is necessary and planned to investigate the causes of these large differences. However, for the intended purposes of TWAVE modeling system, these non-calibrated TWAVE modeling results are comparable to those reported by previous modeling studies (Phadke et al. 2003; Cheung et al. 2003).

The wave and wind parameters are plotted in Figure 16 at the offshore sta G08, located just south of the Poipu Beach. Poipu Beach is located on the southeast coast of Kauai. Poipu Beach received some of the largest waves during Hurricane Iniki because of its location with respect to the storm track. The maximum wind and wave heights occurred during the landfall at 00:00 GMT on 12 September 1992.

As the storm makes landfall, the wave and wind directions change sharply. The mean wave direction is a better parameter than the peak wave direction for nearshore wave transformation as it appears to be more stable and follows closely the wind direction. Figure 17a shows the nearshore water levels at the sta I01 which is located south of Poipu Beach. The astronomical tide was calculated using the Oregon State Tidal Prediction Software and the Hawaii regional tidal database. The storm surge was calculated using only the atmospheric pressure (barometric tide). The storm landfall occurred shortly before the high tide stage. The offshore wave conditions were transformed to the nearshore using WAVETRAN (Gravens et al. 1991). The nearshore wave height and wave period are shown in Figure 17b.

The maximum wave heights occurred on 00:00 GMT on 12 September 1992 at the offshore station. Because of the influence of the wave direction, the maximum wave height at the nearshore station occurred 1 hr later. Most of the wave energy is concentrated to within a 16-hr period centered on the landfall time of storm. Port Allen is located in Hanapepe Bay on the south central coast of Kauai. Water levels were recorded in Port Allen at NOAA tide gauge sta 1611347. The measured and calculated water levels at Port Allen are shown in Figure 18. The Total water level is the sum of the astronomical tide, storm surge, and setup (wind plus wave setup). The computed and measured total water levels show a good agreement. The time shift in the peak water levels might be due to the simplified storm surge calculation used in this example.

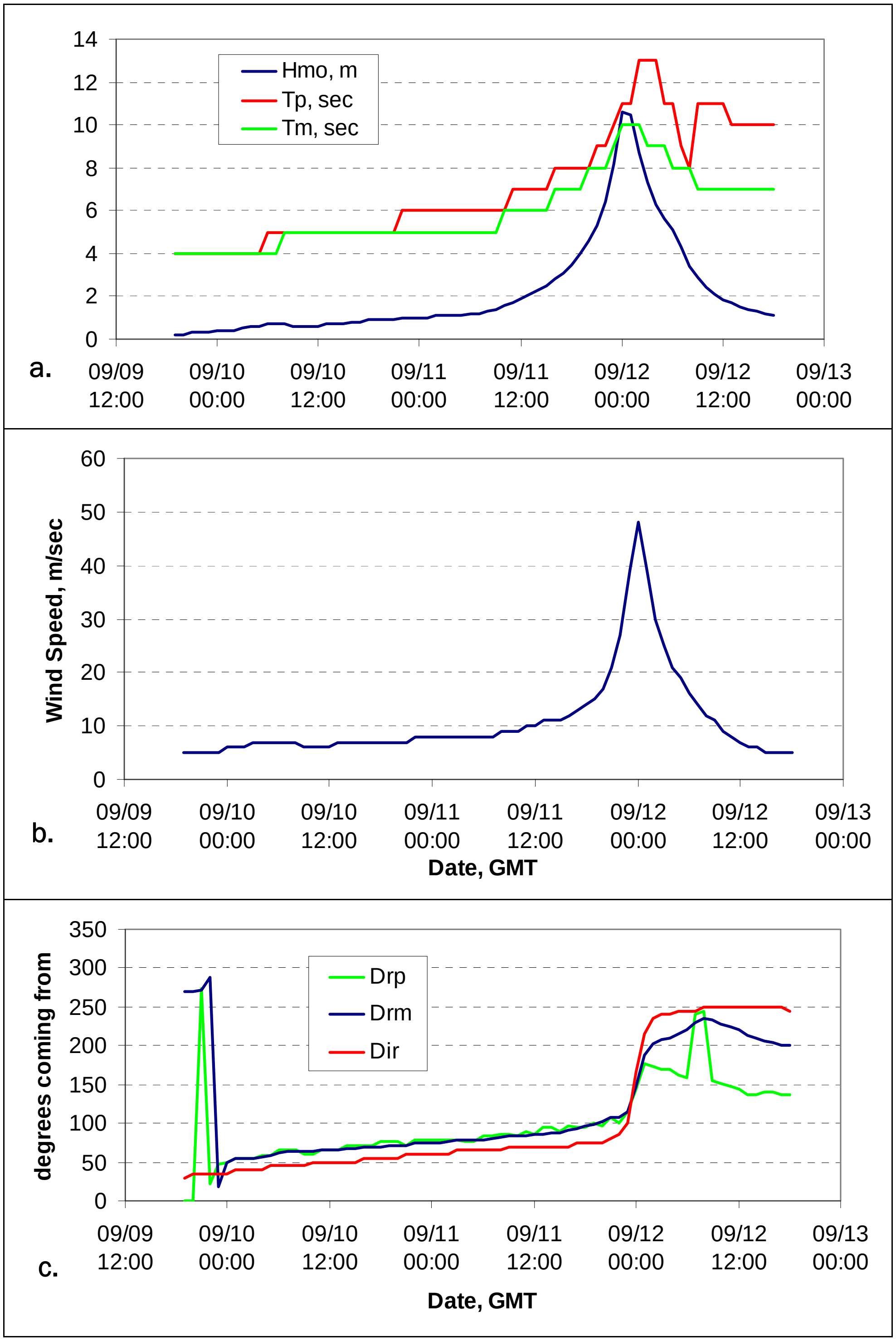


Figure 16. Offshore sta G08 during Hurricane Iniki. (a) Zeroth moment wave heights (H_{mo}), peak wave periods (T_p), and mean wave period (T_m), (b) wind speed, and (c) peak wave period (D_{rp}), mean wave period (D_{rm}), and wind direction (Dir).

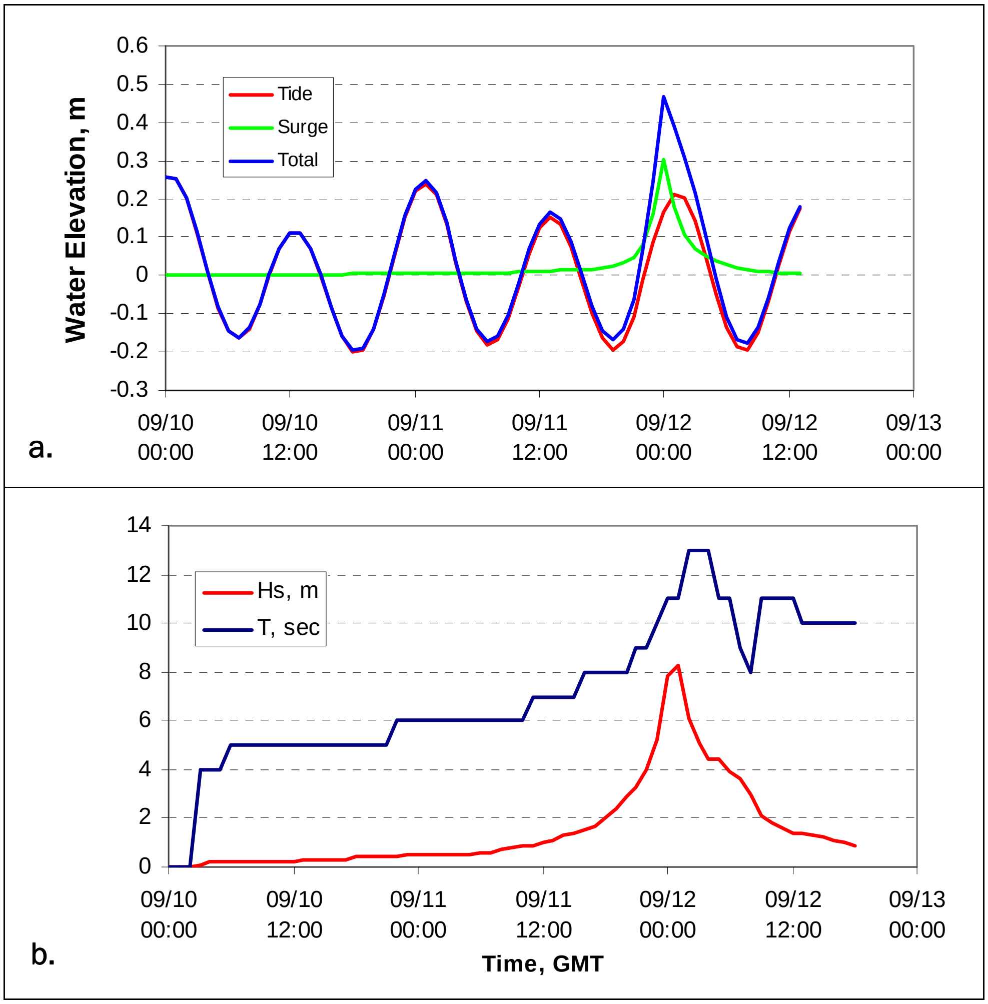


Figure 17. Tide, surge and combined surge, and tide water elevations: (a) wave heights and periods, (b) at nearshore sta I01.

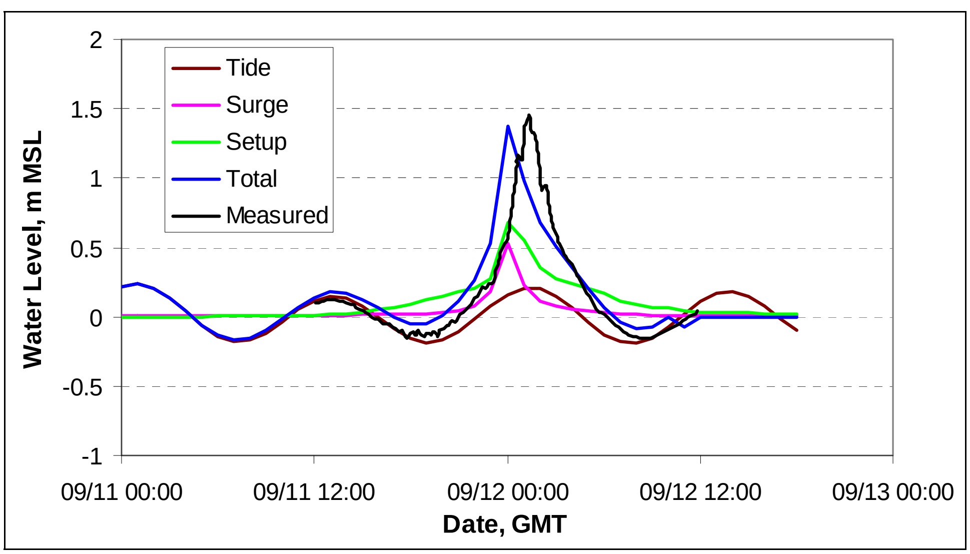


Figure 18. Comparison of measured and computed water levels and Port Allen, Kauai during Hurricane Iniki.

Because Poipu Beach is located on the southeast coast of Kauai, it received some of the largest waves during Hurricane Iniki. A time series of water levels, wave parameters, and 2-percent exceedance water levels (*WL*2%) at Poipu Beach are shown in Figure 19. Here variables d_r and H_r are the water depth and wave height over the reef top. Figure 19 shows the maximum coastal inundation occurred during storm landfall at 02:00 GMT on 12 September 1992.

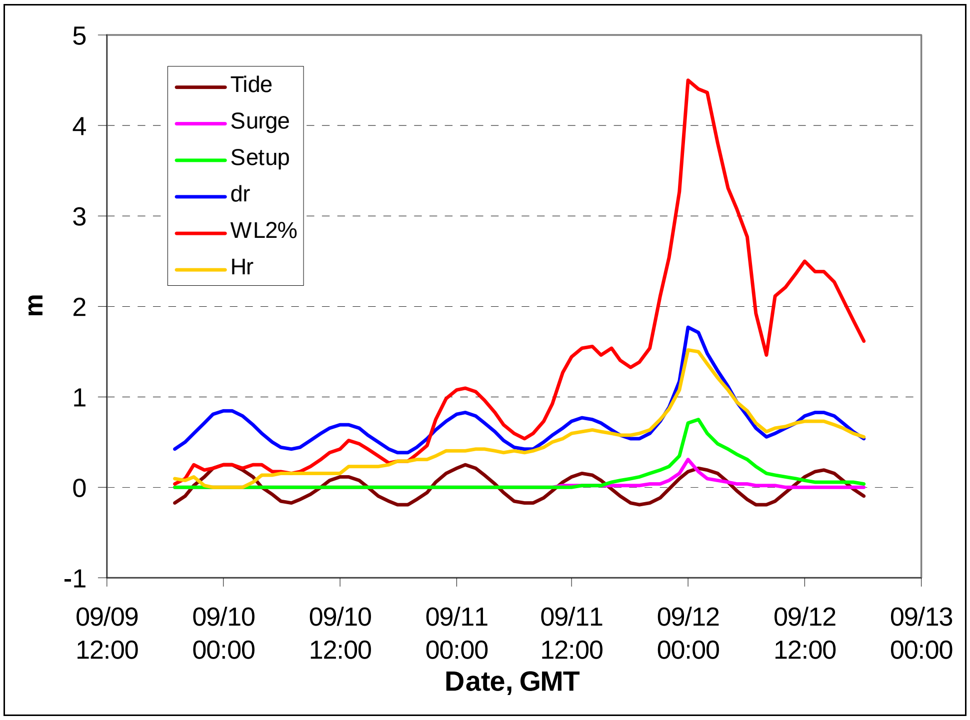


Figure 19. Time series statistics at Poipu Beach during Hurricane Iniki.

The WAV1D model offers an efficient method for obtaining the time period of maximum coastal inundation. This significantly reduces the number of simulations required using more computationally intensive 1D or 2D models. Although the maximum storm surge and wave setup occurred near high tide for Hurricane Iniki, this is not always the case for storm events. The wave runup is a nonlinear function of water levels, wave heights, and wave periods. By using simple empirical formulas, WAV1D can predict runup and inundation for the entire storm duration and a reasonably accurate estimate of time for the highest coastal flooding to occur.

The cross-shore variation of wave height (*H_s*), wave breaking (*Q_b*), and setup (*eta*) at Poipu Beach as calculated from WAV1D are shown in Figure 20a. The bathymetric profile is shown in Figure 20b. Here Q_b is to the fraction of breaking waves whose value varies between 0 and 1. Near-shore waves propagating over the reef shoal and increase in height, and eventually the breaker zone starts at about 400 m from the shoreline. The wave height and setup over the reef as predicted from WAV1D are approximately 1.5 and 0.6 m, respectively. The maximum water level predicted by WAV1D using the empirical formula of Mase (1989) is 5.5 m, which compares well to the measured maximum runup from the debris line of 4-6 m reported by Fletcher et al. (1995).

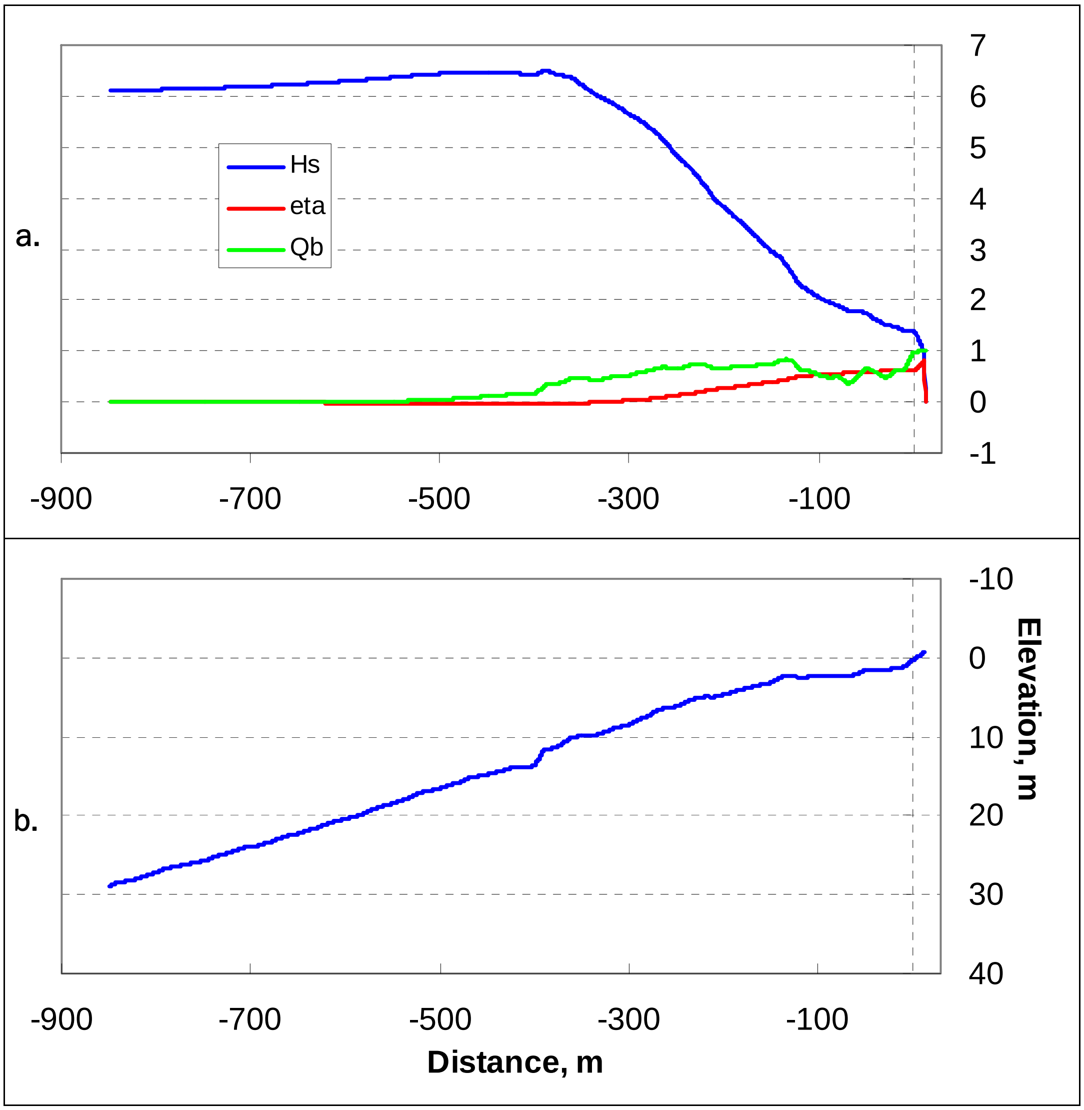


Figure 20. Wave transformation over Poipu reef for Hurricane Iniki calculated from WAV1D on 12 September 1992, 00:00 GMT.

The nearshore transformation was also simulated using BOUSS-1D for the (wave and water level conditions at the time of maximum coastal flooding as predicted by WAV1D. The calculated cross-shore variation of wave height (H_s) and setup (*eta)* are shown in Figure 21. The results from WAV1D and BOUSS-1D models are relatively similar. One difference is that the BOUSS-1D model does not predict an increase in wave height before breaking. This may be due to the values of model parameters used in these simulations. The predicted wave height and setup over the reef from BOUSS-1D are 1.5 and 0.4 m, respectively, and similar to those estimated by WAV1D model.

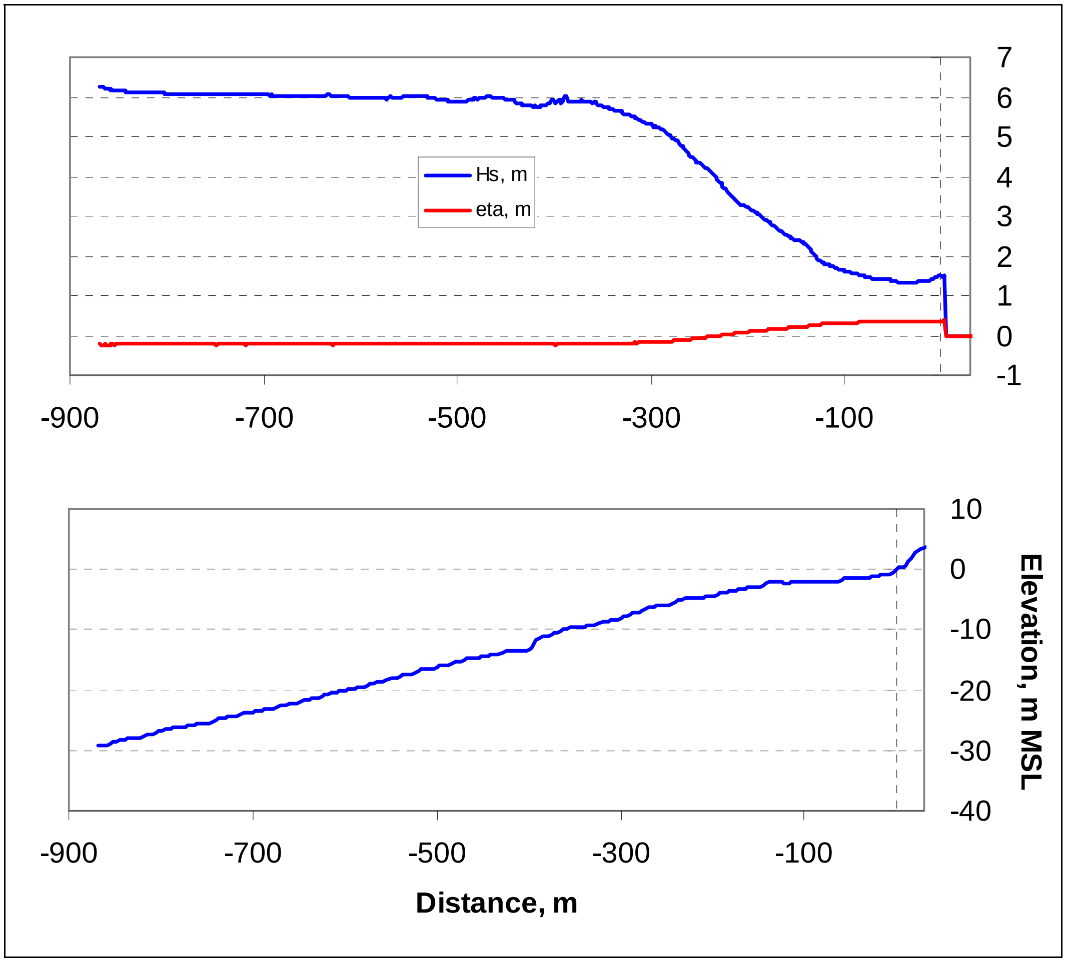


Figure 21. Wave transformation over Poipu reef for Hurricane Iniki calculated from BOUSS-1D on 12 September 1992, 00:00 GMT.

Example 2: Typhoon Russ (Guam)

Typhoon Russ passed approximately 70 km south coast of the island of Guam on 20 December 1990, moving from east to west and with maximum 1-min sustained wind speeds of 125 knots. This powerful storm produced sustained wind speeds in excess of 100 knots on Guam during its passage along a track of about 35 miles south of the U.S. Territory of Guam (Figure 22). Modeling results are shown in Figure 23 at sta I01 for the section of Guam coast that lies between Inarajan Bay and Agfayan Bay in the southeastern part of the island. This section of coast is directly exposed to typhoons approaching the island from the east. The coastal roads and properties in this area experience damage from typhoon inundation.

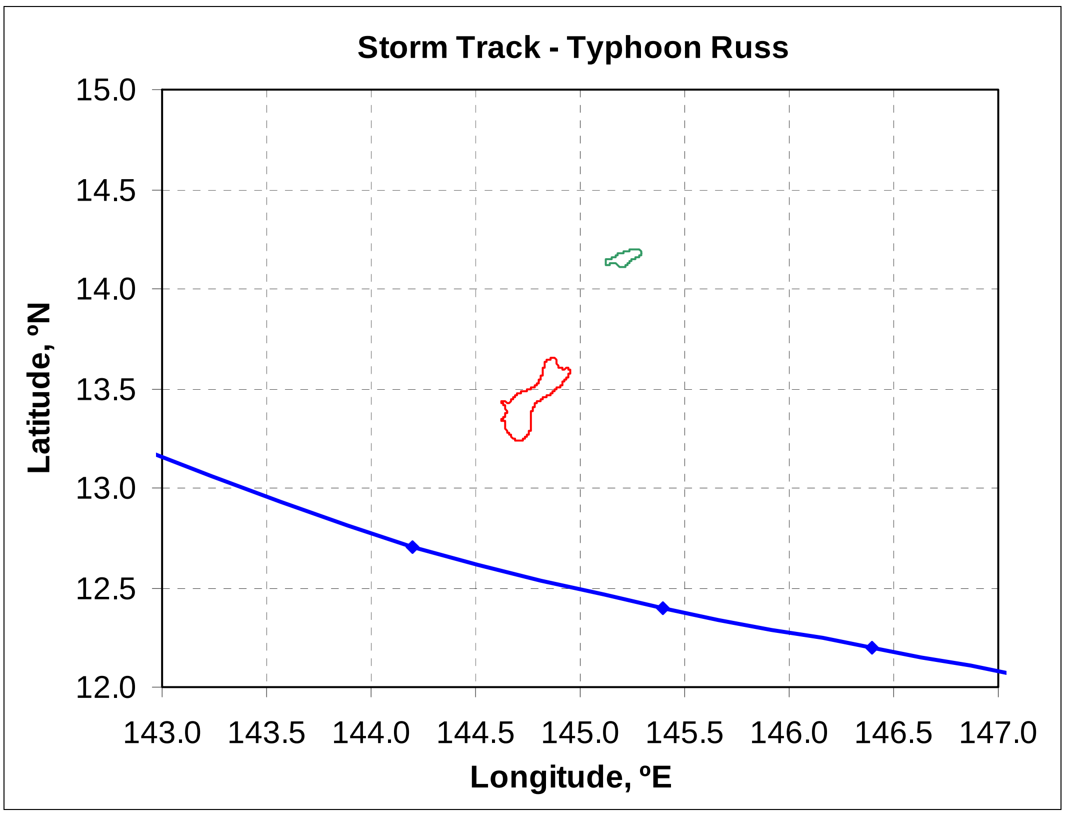


Figure 22. Storm track for Typhoon Russ (red line indicates coastline for Guam, green line indicates coastline for Rota).

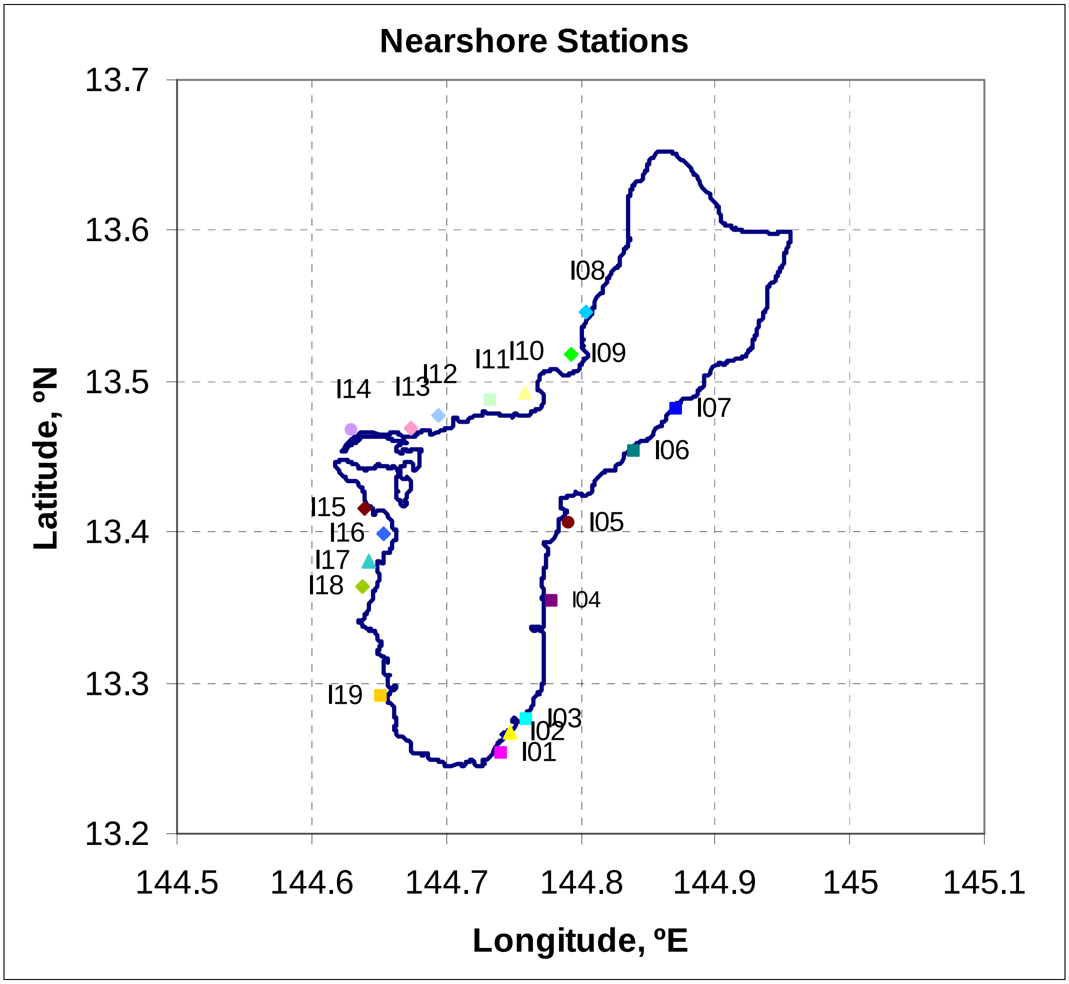


Figure 23. Island of Guam showing location of nearshore stations

Figure 24 shows the contour map of the maximum significant wave heights at each WISWAVE grid cell. This figure is plotted using the Excel worksheet *HMAX*. The maximum calculated significant wave heights reached 18 m in the southeast of Guam, and 7.5-10 m close to the shore.

Figure 25 shows the time series of wave heights, periods and directions at the offshore sta G26. This station is located on the southeast side of the island of Guam in the Inarajan Bay. The maximum calculated offshore significant wave heights at G26 are 15 m, and the peak wave period and direction are 12 sec and 160 deg, respectively.

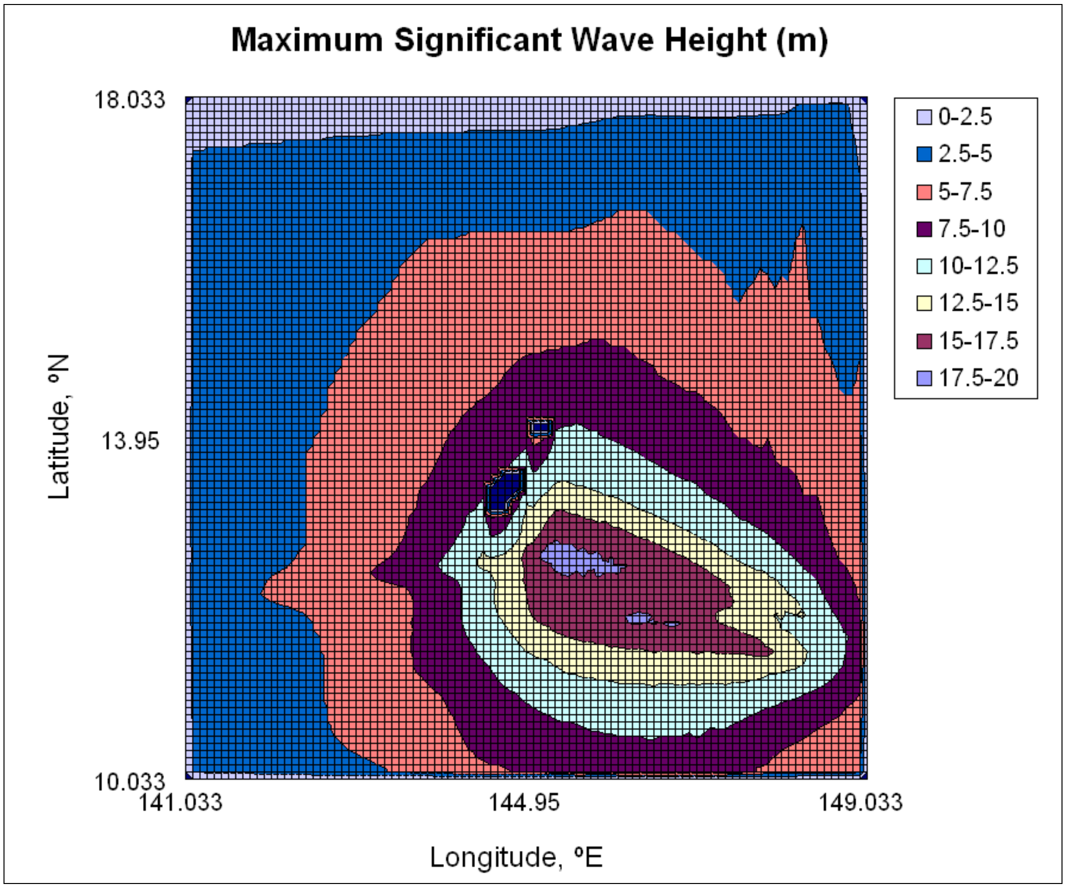


Figure 24. Maximum significant wave heights during Typhoon Russ near the island of Guam.

Hourly wave and water level conditions are plotted in Figure 26 at near-shore sta I01. The wave conditions were calculated using a spectral wave transformation from the offshore sta G26 to the nearshore sta I01 by assuming straight and parallel bathymetric contours (see Deep- to Shallow-Water Transformation section in Chapter 4). With the type of offshore to nearshore transformation performed, the significant wave heights were reduced from 15 to 9 m. The peak storm surge coincided with the low water astronomical tides at 16:00 GMT on 20 December 1990.

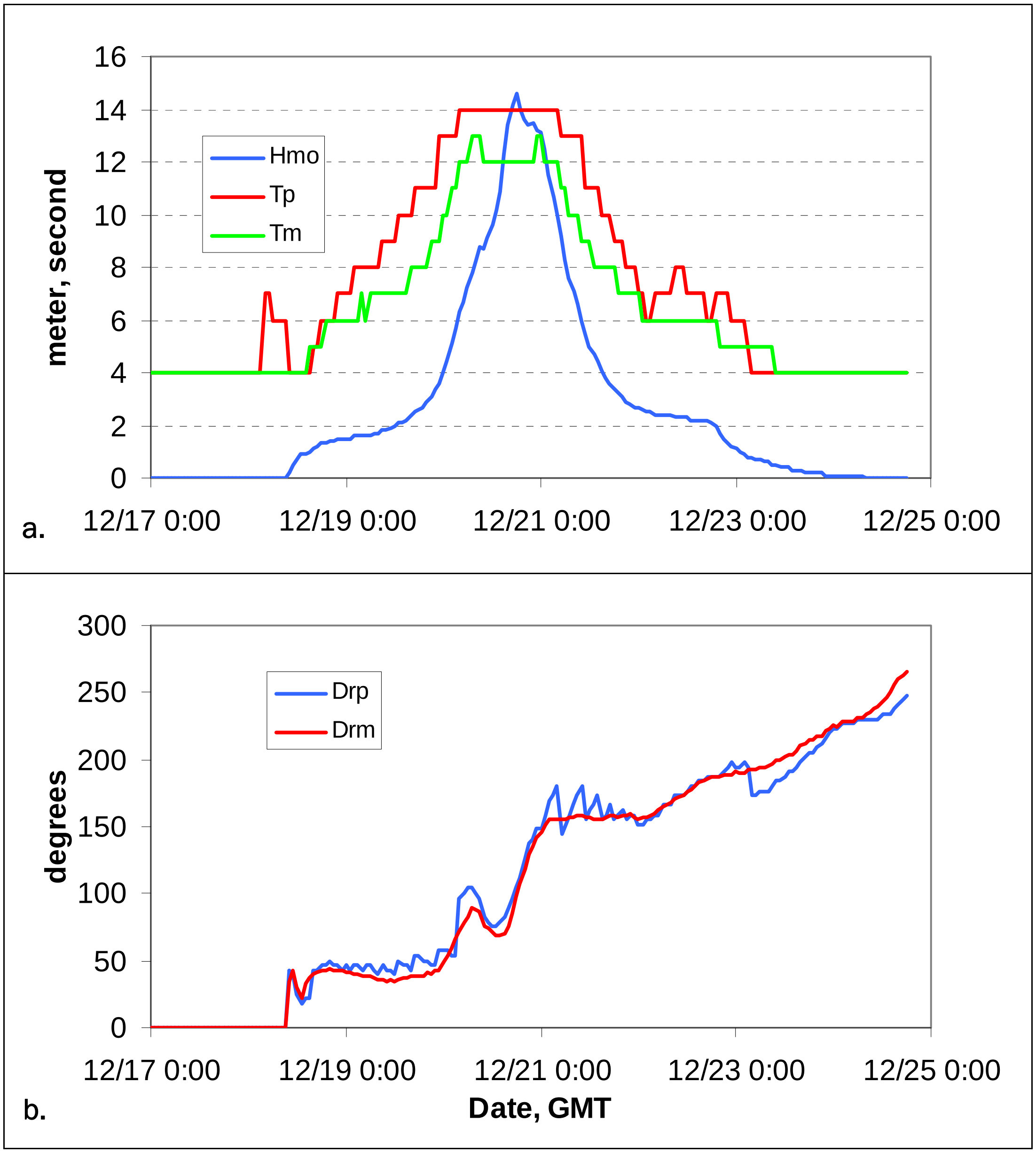


Figure 25. Wave conditions at Offshore sta G26: (a) Zeroth moment wave heights (H_{mo}), mean wave period (T_m), and peak wave period (T_p), (b) peak wave direction (D_{rp}) and mean wave direction (D_{rm}).

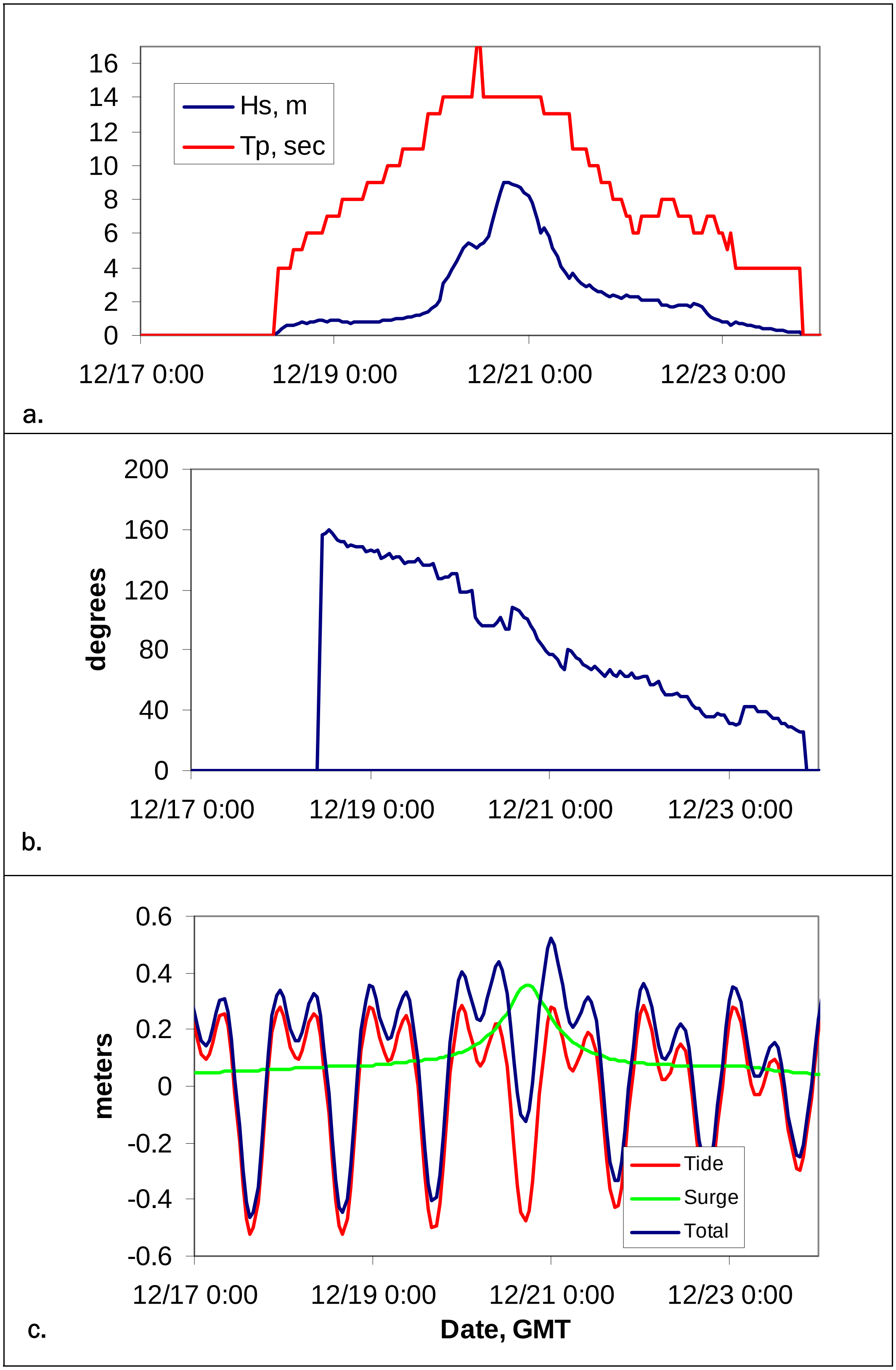


Figure 26. Nearshore sta I01 near Inarajan Guam during Typhoon Russ: (a) wave heights and periods, (b) wave direction, and (c) tide, surge and combined surge and tide water elevations.

For the transect P001, the hourly time series of tides, storm surge, reef top water depths, significant wave height, and 2-percent exceedance water levels as calculated from WAV1D are shown in Figure 27. This figure illustrates that the maximum coastal inundation could occur at times different than the time of peak storm surge. For Typhoon Russ, the computed storm surge peaked at 16:00 GMT on 20 December, whereas the calculated maximum coastal inundation occurred 6 hr later.

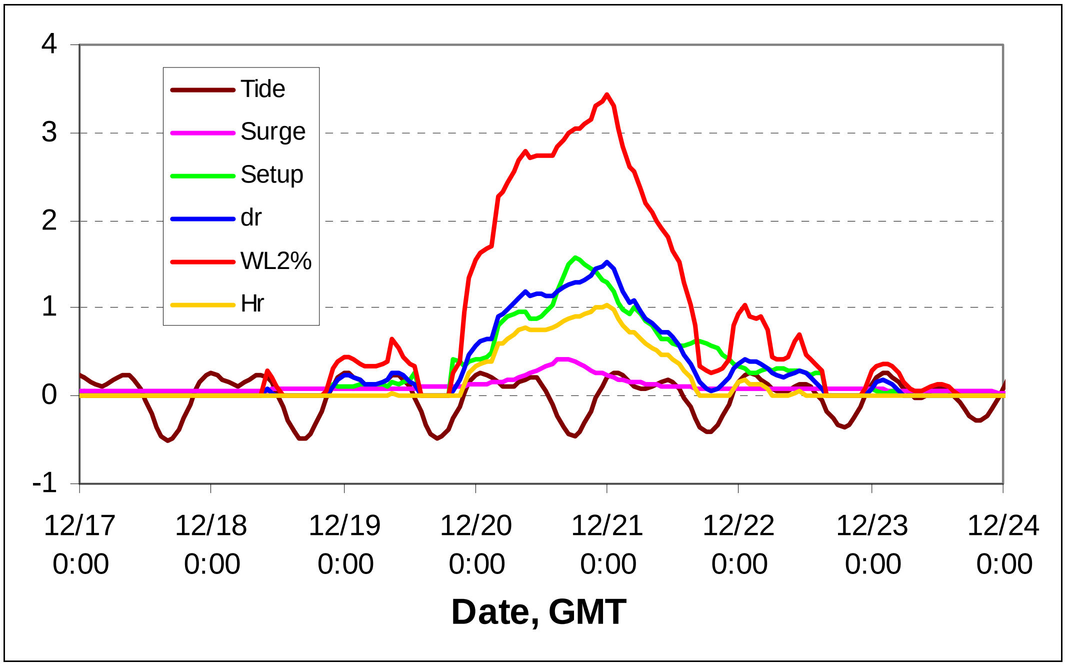


Figure 27. Tide, surge, wave setup and runup at transect P001 near Inarajan Guam during Typhoon Russ.

The cross-shore variation of the significant wave height and mean water level for transect P001 is shown in Figure 28. The significant wave height and mean water level over the reef are approximately 1.0 and 1.3 m, respectively. The strongest wave breaking, indicated by the fraction of breaking waves Q_b, occurs at the reef edge (125 m from the shoreline), and at the beach face, but wave breaking starts as far as 350 m from the shore at approximately 15-m water depth.

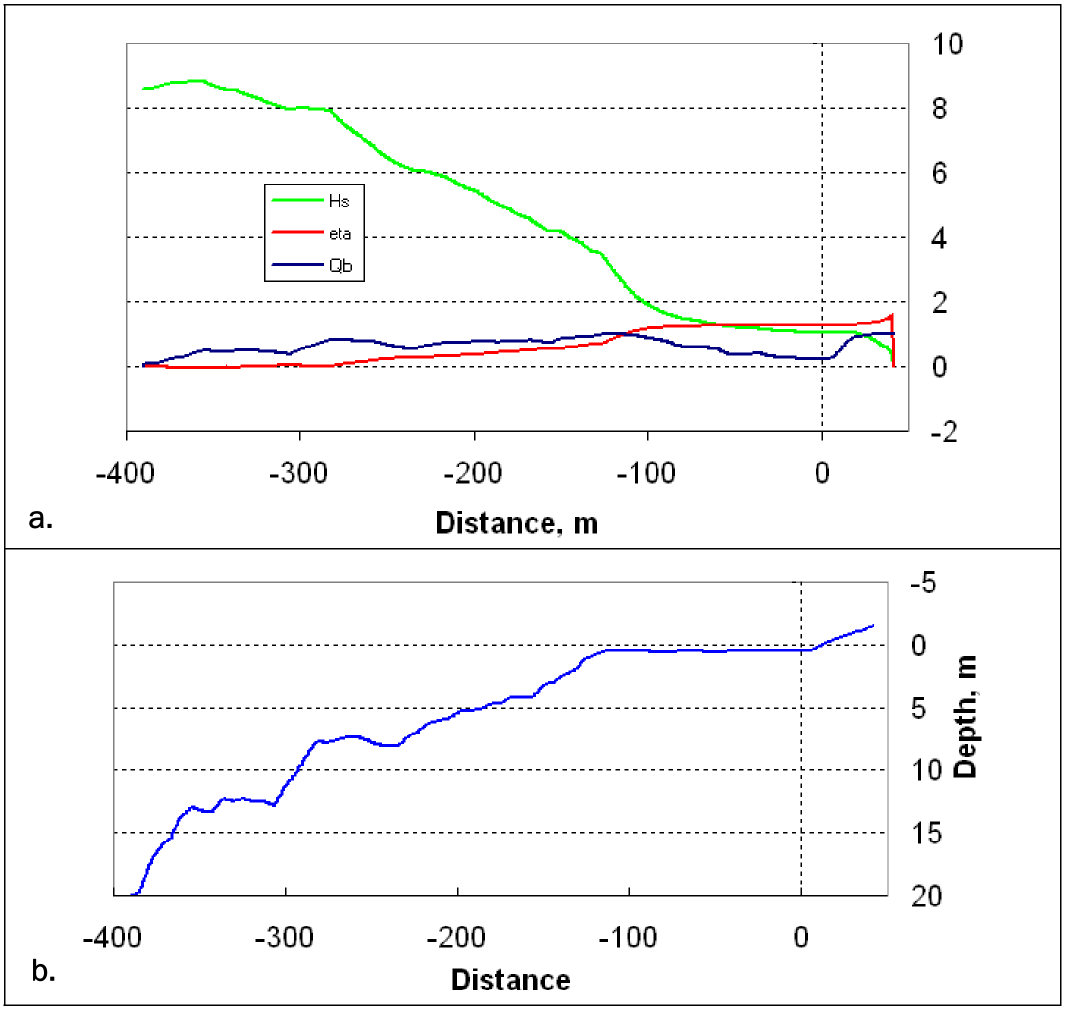


Figure 28. Transect P001 during period of maximum water level reached by runup near Inarajan Guam during Typhoon Russ on 12 December 1990, 00:00 GMT: (a) significant wave height H_s (m), setup *eta* (m) and fraction of breaking waves Q_b and (b) still water depths.

7 Summary and Conclusions

A user-friendly modeling package called TWAVE is described in this report. This modeling system is developed for tropical cyclones, and provides engineers and decision-makers estimates of associated winds, waves, storm surges, and resulting coastal inundation levels. TWAVE consists of a family of computational models, and the system is implemented in the Microsoft Excel for graphical interface. This report serves as the User's Guide and presents description of the TWAVE methodology, input files, output files, and two example applications.

The TWAVE system provides users with models of varying complexity and accuracy for calculating winds, waves, and coastal inundation. Different levels of complexity are provided for different types of applications such as modeling past storm events (hindcast), forecast of future storms, and hypothetical storms. Less resource-demanding models that run fast with a low-order accuracy may be used to perform quick simulations for decision-making and determine if further modeling using models of higher accuracy is warranted. For example, TWAVE parametric models may be used to calculate rough estimates of coastal inundation at hourly intervals, and the approximate time of the most severe inundation to occur. The user may then choose to run other TWAVE models with higher accuracy (physics-based models with fewer free parameters that are resource-demanding) to pinpoint the locations and times of the flooding and severity of coastal inundation. This approach will allow users to reduce the number of numerical simulations required with comparatively more resource-demanding numerical models.

Two example applications presented in this report are intended to illustrate the usage of TWAVE in practical applications. Computed values of wave heights, water levels, wave setup, and wave runup from TWAVE are used to calculate the extent of island flooding, and compared to the post-storm damage survey records. The estimates are reasonable in spite of several uncertainties involved, and demonstrate the usefulness of TWAVE for quantitative flooding of coastal areas. Guidance is provided in the example applications for selecting critical modeling parameters including for determining the breaking wave height H_b and stable wave height parameter used in WAV1D model. In the next update of TWAVE model, field and laboratory data will be used to calibrate models and parameters for breaker types, reef characteristics (reef surface irregularities and roughness), and wind conditions. The integrated set of offshore and near-shore models for winds, tides, waves, and flooding as implemented in the TWAVE modeling system constitute a useful predictive engineering tool for planning and emergency response management of the tropical storms that affect islands in both the Pacific Ocean and Caribbean Sea. TWAVE can also be used in other areas of the U.S. coasts and engineering studies concerned with the design of shore and wetland protection systems such as the barrier islands, levees, and coastal navigation and harbor structures.

In closing, although TWAVE is currently configured for the U.S. Territory of Guam and Kauai Island, HI, it can be easily adapted to other islands or coastal applications for prediction and risk assessment of hurricane and typhoon-induced coastal flooding. Presently, TWAVE has been validated against measured winds, waves, and coastal inundation records obtained for Hurricane Iniki that made landfall on the island of Kauai, HI, in the morning of 12 September 1992. Even though there were no data available for Typhoon Russ that impacted the U.S. Territory of Guam Island, this storm event is also simulated to demonstrate applicability and capabilities of TWAVE to other islands and storm types (typhoons). For Hurricane Iniki, the mean wave periods as compared to the buoys data were off approximately 4 sec, wave heights differences were under-predicted about 2m and over-predicted up to 3m, and TWAVE results lagged the surge peak. The observed lag in the phase gave rise to an associated lag in the peak surge estimate. Additional validation is necessary and planned to investigate potential causes of these differences. Overall, the non-calibrated modeling results from TWAVE are comparable to those reported by previous modeling studies.

This is a manual for the TWAVE model, not a full assessment of the model's abilities, which is a task that is just beginning, now that the model is operational. The TWAVE modeling system is expected to evolve and be improved as it is used in engineering projects. TWAVE will be calibrated with additional field observations in progress. Other numerical models and different engineering methods may be incorporated into TWAVE as these validations warrant. The feedback and suggestions from the users community will be used in the future revisions of TWAVE. Please direct inquiries and suggestions to the attention of authors.

Demirbilek, Z., and O. G. Nwogu. 2007. *Boussinesq modeling of wave propagation and runup over fringing coral reefs, model evaluation report*. ERDC/CHL TR-07-12. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Demirbilek, Z., and V. Panchang. 1998. *CGWAVE: A coastal surface water wave model of the mild slope equation*. Technical Report CHL-98-26. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Demirbilek, Z., O. G. Nwogu, and D. L. Ward. 2007. *Laboratory study of wind effect on runup over fringing reefs, Report 1: Data report*. ERDC/CHL TR-07-4. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Demirbilek, Z., O. G. Nwogu, D. L. Ward, and A. Sanchez. 2008. *Wave transformation over reefs: Evaluation of one-dimensional numerical models*. ERDC/CHL TR-08-17. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Demirbilek, Z., A. Zundel, and O. Nwogu. 2005a. *BOUSS-2D wave model in the SMS: I. Graphical interface*. ERDC/CHL CHETN-I-69. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

______. 2005b. *BOUSS-2D wave model in SMS: II. Tutorial with examples*. ERDC/CHL CHETN-I-70. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Egbert, G., and S. Erofeeva, S. 2002. Efficient inverse modeling of barotropic ocean tides. *Journal of Atmospheric and Oceanic Technology* 19:183-204.

Fletcher, C. H., B. M. Richmond, G. M. Barnes, T. A. Schroeder. 1995. Marine flooding on the coast of Kauai during Hurricane Iniki: Hindcasting inundation components and delineating washover. *Journal of Coastal Research* 11(1):188-204.

Georgiou, P. 1985. *Design wind speeds in tropical cyclone regions*. PhD Thesis, University of Western Ontario, 295 p.

Gerritsen, F. 1980. Wave attenuation and wave setup on a coastal reef. *Proceedings 17th International Conference on Coastal Engineering*, Sydney, Australia. New York: ASCE, 444-461.

Gourlay, M. R. 1994. Wave transformation on a coral reef. *Coastal Engineering 23*:17-42.

______. 1996a. Wave set-up on coral reefs. 1. Set-up and wave-generated flow on an idealized two dimensional horizontal reef. *Coastal Engineering* 27:161-193.

______. 1996b. Wave set-up on coral reefs. 2. Set-up on reefs with various profiles. *Coastal Engineering* 28:17-55.

______. 2005. Wave-generated flow on coral reefs-an analysis for two-dimensional horizontal reef-tops with steep faces. *Coastal Engineering* 52:353-387.

Grasmeijer, B. T., and B. G. Ruessink. 2003. Modeling of waves and currents in the near-shore: parametric vs. probabilistic approach. *Coastal Engineering* 49:185-207.

Gravens, M. B., N. C. Kraus, and H. Hanson. 1991. *GENISIS: Generalized model for simulating shoreline change*. Coastal and Hydraulics Laboratory Technical Report CERC-89-19. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Harper, B. A., and G. J. Holland. 1999 An updated parametric model of the tropical cyclone. *Proceedings 23rd Conference Hurricanes and Tropical Meteorology*. Dallas, TX: American Meteorological Society, 10-15.

Headquarters, U.S. Army Corps of Engineers. 2006. *Coastal Engineering Manual*. EM 1110-2-1100. Washington, DC.

Hedges, T. S., and H. Mase. 2004. Modified Hunt's equation incorporating wave setup. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 130(3):109-113.

Holland, G. J. 1980. An analytic model of wind and pressure profiles in hurricanes. *Monthly Weather Review* 108(8):1,212-1,218.

Hubertz, J. A. 1992. *User's guide to the Wave Information Studies (WIS) wave model, Version 2.0*. WIS Report 27. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Hughes, L. A. 1952. On the low level wind structure of tropical cyclones. *Journal of Meteorology* 9:422–428.

Janssen, T. T., and J. A. Battjes. 2007. A note on wave energy dissipation over steep beaches. *Coastal Engineering* 54:711-716.

Jensen, R. E. 1983. *Methodology for the calculation of a shallow-water wave climate. Wave Information Study Report 8*. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Knaff, J. A., and R. M. Zehr. 2007. Reexamination of tropical cyclone wind-pressure relationships. *Weather and Forecasting* 22:71-88.

Koba, H. T., S. A. Hagiwara, and S. Aakashi. 1990. Relationships between CI number from Dvorak's technique and minimum sea level pressure or maximum wind speed of tropical cyclones (in Japanese). *Journal of Meteorological Research* 42:59-67.

Komar, P. D., and M. K. Gaughan. 1973. Airy wave theory and breaker height prediction. *Proceedings of the 13th Coastal Engineering Conference*, ASCE, 405-418.

Landsea, C. W., and C. Anderson, N. Charles, G. Clark. 2004. The Atlantic hurricane database re-analysis project: Documentation for 1951–1910. In: *Alterations and additions to the HURDAT. Hurricanes and Typhoons Past, Present and Future*. R. J. Murname and K.-B. Liu, eds., Columbia University Press, 177-221.

Larson, M., and N. C. Kraus. 1991. Numerical model of longshore current for bar and trough beaches. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 117(4):326-347.

Liu, W. T., K. B. Katsaros, and J. A. Businger. 1979. Bulk parameterizations of air-sea exchanges of heat and water vapor including the molecular constraints at the interface. *Journal of the Atmospheric Sciences* 36(9):1,722-1,735.

Longuet-Higgins, M. S., and R. W. Stewart. 1964. Radiation stress in water waves: A physical discussion with applications. *Deep Sea Research* 11:529-562.

Lowe, R. J., J. L. Falter, M. D. Bandet, G. Pawlak, M. J. Atkinson, S. G. Monismith, and J. R. Koseff. 2005. Spectral wave dissipation over a barrier reef. *Journal of Geophysical Research* 110(C04):1-16.

Luettich, R. A., J. J. Westerink, and N. W. Scheffner. 1992. *ADCIRC: An advanced three-dimensional circulation model for shelves, coasts, and estuaries; Report 1, theory and methodology of ADCIRC-2DDI and ADCIRC-3DL*. Dredging Research Program Technical Report ERDC/CHL TR DRP-92-6, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Mase, H. 1989. Random wave runup height on gentle slope. *Journal of Waterway, Port, Coastal and Ocean Engineering* 115(5):649-661.

Massel, S. R., and R. M. Brinkman. 2001. Wave-induced set-up and flow over shoals and coral reefs, Part 1. A simplified bottom geometry case. *Oceanologia* 43:373-388.

Massel, S. R., and M. R. Gourlay. 2000. On the modeling of wave breaking and set-up on coral reefs. *Coastal Engineering* 39:1-27.

Militello, A., N. W. Scheffner, and E. F. Thompson. 2003. *Hurricane induced stage-frequency relationships for the territory of American Samoa*. Coastal and Hydraulics Laboratory Technical Report CHL-98-33 (revised). Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Nielson, P. 1992. *Coastal bottom boundary layers and sediment transport*. World Scientific, Singapore, 324 p.

Nwogu, O. 2006. Personal communication with Edward Thompson, University of Michigan, Department of Architecture and Marine engineering, Ann Arbor, MI 48109.

Nwogu, O., and Z. Demirbilek. 2001. *BOUSS-2D: A Boussinesq wave model for coastal regions and harbors*. ERDC/CHL TR-01-25. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Phadke, A. C., C. D. Martino, K. F. Cheung, and S. H. Houston. 2003. Modeling of tropical cyclone winds and waves for emergency management. *Ocean Engineering* 30(4):553–578.

Rankine, W. J. M. 1901. *A Manual of Applied Mechanics*. 16th ed. Charles Griff and Co., 680 p.

Resio, D. T., and W. Perrie. 1989. Implications of an f-4 equilibrium range for wind-generated waves. *Journal of Physical Oceanography* 19:193-204.

Ruessink, B. G., D. J. R. Walstra, and H. N. Southgate. 2003. Calibration and verification of a parametric wave model on barred beaches. *Coastal Engineering* 48(3):139-149.

Sánchez, A., J. Smith, Z. Demirbilek, S. Bock. 2007. Combined wind and waves over a reef. Proceedings 10th International Workshop, Wave Hindcasting and Forecasting and Coastal Hazard Symposium. Oahu, HI.

Seelig, W. N. 1983. Laboratory study of reef-lagoon system hydraulics. *Journal of Waterway, Port, Coastal and Ocean Engineering* 109(4):380-391, ASCE.

Smith, J. M. 1993. *Nearshore wave breaking and decay*. Coastal Engineering Research Center Technical Report CERC-93-11. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Smith, J. M., A. R. Sherlock, and D. T. Resio. 2001. *STWAVE: Steady-state spectral wave model: User's manual for STWAVE*. Version 3.0. ERDC/CHL SR-01-01. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Stive, M. J. F., and H. J. De Vriend. 1994. Shear stresses and mean flow in shoaling and breaking waves. *Proceedings Coastal Engineering*. New York: ASCE, 594-608.

Thompson, E. F. 2005. *A physical model study for investigation of wave processes over reefs*. Coastal Hydraulics Laboratory Unpublished Letter Report. Vicksburg, MS: U.S. Army Engineer and Research Development Center.

Thompson, E. F., and V. J. Cardone. 1996. Practical modeling of hurricane surface wind fields. *Journal of Waterway, Port, Coastal and Ocean Engineering* 122(4):195-205.

Thompson, E. F, and N. W. Scheffner. 2002. *Typhoon-induced stage-frequency and overtopping relationships for the commercial port road, Territory of Guam*. ERDC/CHL TR 02-01. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Thornton, E. B., and R. T. Guza. 1983. Transformation of wave height distribution. *Journal of Geophysical Research* 88(C10):5925-5938.

Tracy, B. A., and A. Cialone. 2004. Comparison of Gulf of Mexico Wave Information Studies (WIS) 2-G hindcast with 3-G hindcasting. *8th International Workshop of Wave Hindcasting and Forecasting*. North Shore, Hawaii.

Willoughby, H. E., R. W. R. Darling, and M. E. Rahn. 2006. Parametric representation of the primary hurricane vortex, Part II: A new family of sectionally continuous profiles. *Monthly Weather Review* 134:1,102-1,120.

Xie, L., S. Bao, L. Pietrafesa, K. Foley, and M. Fuentes. 2006. A real-time surface wind forecasting model: Formulation and verification. *American Meteorological Society* 134(5):1,355-1,370.

Zhao, L., V. Panchang, W. Chen, Z. Demirbilek, and N. Chhabbra. 2001. Simulation of wave breaking effects in two-dimensional elliptic harbor wave models. *Coastal Engineering* 42:359-373.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
January 2009

2. REPORT TYPE
Final report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

TWAVE: A Modeling System for Flooding and Inundation of Islands by Tropical Storms

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Alejandro Sánchez, Zeki Demirbilek, and Jane M. Smith

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center
Coastal and Hydraulics Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/CHL TR-09-2

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Headquarters, U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report, the first of a series, describes the coastal modeling package TWAVE (Typhoon and WAVE) developed under the Surge and Wave Island Modeling Studies (SWIMS) project capable of modeling tropical cyclone winds, waves, storm surge, and coastal inundation. The TWAVE flood and inundation package is a practice-oriented engineering modeling tool. The first version of TWAVE is described in this report and will be updated based on user feedback in subsequent reports and as new modeling capabilities become available. The objective of this research is to develop a system with multiple levels of complexity that is suitable for applications such as hindcast, forecast, and hypothetical storms. TWAVE is a personal computer based modeling system and uses Microsoft Excel® to organize and visualize input and output data. The package includes three wind models coupled to a deepwater spectral wave model and a parametric wave model with several options for calculating reef top wave heights, wave setup, and runup. These calculations range from simple empirical formulations to a fully nonlinear Boussinesq wave model.

(Continued)

15. SUBJECT TERMS

See reverse.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		89	

14. ABSTRACT (Concluded)

TWAVE modeling system is currently configured for the U.S. Territory of Guam and the island of Kauai, HI, but can easily be configured for other locations. A full description of the TWAVE package of programs and input, and output are described in this report to assist users who interested in adopting the system to their specific needs. TWAVE is a modular system, and this makes it possible to add new components and replace existing modules as necessary. TWAVE modeling package is validated using measured offshore winds and waves, and coastal inundation records for Hurricane Iniki at Poipu beach on the island of Kauai, HI. Modeling estimates generally compare reasonably well with measurements. The calculated offshore winds, waves, and coastal inundation estimates compare favorably to data. Although there were no data for validation on the island of Guam, TWAVE capabilities are also demonstrated for Typhoon Russ.

15. SUBJECT TERMS

Barometric, astronomical tides
Boussinesq model
Coastal inundation
Cross-shore profiles
Cyclone, typhoons, hurricanes
Flooding and inundation
Fringing reefs
Hindcast, forecast, storms
Numerical wave modeling
Offshore winds, waves, surges
Sheltering, shoreline orientation
Spectral wave models
Tropical islands
Wave setup and runup
Wave transformation